AN ASSESSMENT OF THE MIXING PERFORMANCE OF SEVERAL ANAEROBIC DIGESTERS USING TRACER RESPONSE TECHNIQUES

RESEARCH PUBLICATION NO. 72

December 1978

Ministry of the Environment

Ontario

The Honourable
Harry C. Parrott, D.D.S.,
Minister

Graham W. Scott,
Deputy Minister

AN ASSESSMENT OF THE MIXING PERFORMANCE

OF SEVERAL ANAEROBIC DIGESTERS USING

TRACER RESPONSE TECHNIQUES

RESEARCH PUBLICATION NO. 72

By:

J. Smart

Wastewater Treatment Section
Pollution Control Branch
Ontario Ministry of the Environment

December, 1978

ABSTRACT

A study was conducted to assess the mixing characteristics of typical modern anaerobic digesters.

Ten different digesters were selected for study, representing extremes in physical size, age and condition, and including most of the types of mixing equipment currently in common use.

Digester sizes varied from 754 m^3 (165,900 gal) to 7667 m^3 (1,690,000 gal) and specific applied nameplate power from 654 W/1000 m^3 (0.02 HP/1000 ft^3) to 6561 W/1000 m^3 (0.25 HP/1000 ft^3). Six digesters were gas mixed and four mechanically mixed.

Digester mixing, measured by tracer response studies, was seen to be rather inadequate, ranging from 10% to 89% dead space, and averaging about 45% dead space. Substrate short-circuiting was seen in four of seven digesters tested for this effect and ranged from 18% to 72% of the sludge substrate input.

Actual, observed hydraulic retention times ranged from 18% to 97% of theoretical values and averaged 65% for all ten test digesters.

No reliable, readily discernable relationships were seen between mixing efficiencies and digester sizes, ages and general conditions, types of mixing equipment installed, and specific applied nameplate power.

From generally accepted literature data, the digesters tested appeared overdesigned, suggesting that maximum digester volume utilization and elimination of substrate short-circuiting by improved design and mixing efficiencies would allow substantially higher applied organic and hydraulic loadings with attendant operating and economic benefits.

TABLE OF CONTENTS

LIST OF FIGURES

CONCLUSIONS

1. Mixing of the anaerobic digesters studied was, in general, grossly inadequate with respect to volume utilization.

2. Several digesters tested showed a propensity for massive substrate short-circuiting, in addition to poor volume utilization.

3. There was no clear cut distinction seen between the mixing performance of mechanical and gas mixed systems.

4. No reliable relationship was seen between specific applied nameplate power and digester mixing performance.

5. Substrate short-circuiting was noted, in one case, to be a function of poor sludge inlet pipework design in addition to poor mixing equipment performance.

6. Substrate short-circuiting was observed, in most cases, to be easily detected visually and olfactorily and, in one case, was accompanied by a very low transfer sludge temperature of $13^{o}C$ ($55^{o}F$).

7. Digester depth profile sampling by removing discrete samples through roof sampling ports, was found to be of little value in assessing mixing performance, while digester exit tracer response measurements provided good appraisals of mixing.

RECOMMENDATIONS

1. Full-scale studies should be conducted to determine the upper organic and hydraulic loading levels possible in the absence of digester dead space and substrate short-circuit, by optimizing mixing in an existing digester.

2. These studies should also attempt to develop a definitive, predictive digester mixing theory to aid designers in future construction and in the "retrofit" of present facilities.

3. Mixing equipment manufacturers should re-examine modern coating technology and/or the increased use of plastic materials in the construction of mixing equipment and allied components, to increase the service life of such equipment in a highly corrosive and erosive environment.

4. In present digester systems, power readings should be taken regularly on mixer drive and/or blower motors. Future design should allow for the installation of permanent ammeters on control panels to provide easy monitoring of mixer power draw.

5. Digester mixing acceptance tests, using tracer techniques, should be a feature or requirement of future design and construction specifications.

1. INTRODUCTION

In the modern high rate anaerobic digestion process which is widely used in Ontario, mixing is a highly important feature which directly affects solids stabilization performance.

Digester mixing is applied towards providing homogeneity of temperature, rapid dispersion of incoming substrate throughout the unit to utilize the total volume, and to minimize solids deposition, scum formation, and short-circuiting of substrate through the system.

Mixing of digester contents is generally accomplished by one of two methods; mechanically, by an electrically driven propellor, or by recirculation of produced digester gas. Additional mixing may be derived from the operation of external heat exchanger recirculating pumps, secondary sludge return to primary tanks, and so on, but the bulk of the mixing action is directly attributable to the installed mixing apparatus.

In general, while past digester performance in Ontario has been satisfactory, there is a growing awareness and evidence that digester mixing is not as efficient as hitherto assumed. This is evidenced by large depositions of solids in fairly short periods of time and by sampling surveys which suggest short-circuiting of raw substrate through some digesters.

The implementation of the Ontario phosphorus removal program in the early 1970's using chemical addition, highlighted problem areas in anaerobic digester operations, including mixing.

In general, phosphorus removal by chemical coagulation has resulted in increased raw sludge or waste activated sludge production rates, producing higher applied loadings to digestion systems, at levels sometimes exceeding the generally accepted upper loading limits for full-scale systems.

The present study was therefore directed towards providing a full-scale practical evaluation of the mixing efficiencies of several digesters with the view of aiding in establishing digester mixing performance guidelines and specifications to upgrade effective digester capacities and performance.

2. LITERATURE REVIEW

Malina (1) shows that as early as 1914, the importance of anaerobic digester mixing was realized and various mixing devices and schemes were employed to break scum blankets and provide sludge mixing.

In early studies, Heukelekian (2) amongst others, showed that digestion performance was improved by shaking or mixing the test unit. His studies used gas production rates, which are a function of solids stabilization performance, as the digestion rate parameter.

Since then, many additional studies have been conducted on the effects of digester mixing showing quite conclusively the benefits obtained. Amongst these, Malina (1), and Sawyer and Grumbling (3) show that accelerated digestion due to mixing provides a reduction in required detention time, an increase in gas production and greater destruction and stabilization of volatile solids.

More recently, Finney and Evans (4) in an attempt to redefine the rate limiting factor in the anaerobic digestion process, advocated high temperature operation at reduced pressures allied with vigorous agitation. They proposed that the process is limited by phase transfer of produced digester gases.

The application of digester mixing has several purposes. Fuhrman (5), and Neuspiel and Morgan (6) show that formation of scum blankets is obviated or minimized in mixed units. Sawyer and Grumbling (3) indicate that mixing of digesters accomplishes three other important factors; the microorganisms are in continuous contact with substrate; the substrate is uniformly distributed and inhibiting materials and biological intermediates such as volatile acids are maintained at minimum levels.

Another benefit, outlined by Dague (7), is the maintenance of uniform temperatures within the digester. Malina (8)(11), Heukelekian and Kaplovsky (9), and Fischer and Green (10) among others, conducted studies showing the importance of uniform temperatures within relatively narrow mesophilic and thermophilic temperature ranges, with Fischer and Greene (10) reporting process inhibition concomitant with rapid temperature variations of $5^{o}F$ *in the thermophilic operating mode.*

These authors included discussion on the microbiological distinction between psychrophilic, mesophilic and thermophilic anaerobic microorganisms and showed the well-defined temperature ranges for each species, beyond which their activity ceased. This highlights the need for effective mixing in digestion to avoid 'cold spots' resulting in localized bacterial inactivity.

While the need for effective anaerobic digester mixing is thus very well documented, little work has been conducted on assessing the actual mixing performance being presently achieved in modern digesters. Lately, however, some interest has been shown in this subject. Tenney and Budzin (12) conducted hydraulic retention time studies using fluoride as a tracer. Their results showed that only an alarming 50% of their test digester volume was actually available for substrate digestion. Studies conducted in Ontario by Monteith and Stephenson (13) on two primary anaerobic digesters, showed that the actively mixed portions of these units were under 25% of the total digester volume, and that massive substrate short-circuiting occurred in one of the test units.

In many studies on the anaerobic digestion process, solids retention time (SRT) has been postulated as being the rate limiting step. Dague (7), Dague, McKinney and Pfeffer (14), and Hindin and Dunstan (15) reported data and experiments showing that sludge retention time was rate limiting with emphasis placed upon methanogenic bacteria regeneration rates being lower than bacteria 'wash-out' rates at low retention periods with a ten-day SRT being considered critical to the process and a three to four day retention causing absolute, irreversible inhibition.

It thus appears obvious that in a digestion system designed for, say, a 25-day retention where the actively utilized volume is only 25% of design, that inhibition of the process to some degree will occur. In addition, in such a system, it is more than likely that large temperature gradients would be experienced with an accompanying imbalance in bacterial populations. Such a system would also be more susceptible to adverse effects due to shock loads by toxic materials in the substrate or by accumulation of digestion intermediates such as volatile acids. Also accompanying poor mixing would be increased solids deposition with time; further reducing active volume.

Recent work reported by Ghosh and Pohland (16) suggests that present digester design is overly conservative, particularly with respect to nominal retention periods. Their bench-scale studies showed that anaerobic microorganism regeneration rates are several orders of magnitude higher than hitherto believed and lower retention periods could thus be used. In the light of the few documented mixing

studies, however, it seems fortuitous that most units appear over-designed as, in practice, the actual active volume is less than the design volume. Their comments possibly reflect a measure of unfamiliarity with full-scale unit operations, and illustrate the inherent danger of extrapolating bench-scale results.

While the hydraulic retention time test method of Tenney and Budzin (12) is simple and practical in evaluating mixing, the model used by Monteith and Stephenson (13) after Cholette and Cloutier (17) and Levenspiel (18) is perhaps of more value as it includes evaluation of substrate short-circuiting in addition to assessing dead space and active volume.

Gloyna and Eckenfelder (19) provided valuable design criteria on mixing equipment in addition to detailed descriptions of the operation and functions of several common digester mixing systems, reflecting the state-of-the-art in these unit operations.

Most literature sources agree, however, that mixing operations, and especially their performance assessment, are, in common with some other unit operations of chemical engineering, rather complex and not widely understood. Coulson & Richardson (20) state that, "the problem of mixing .... has proved one of the most intractable of all the unit operations of chemical engineering and the vast majority of industrial equipment is still designed from experience rather than from any agreed fundamental theory. There is at present no theoretical standard by which the performance of the mixer can be judged ....".

While these comments are general, they may have particular emphasis when directed towards the problems of anaerobic digester mixing, due to the size of these units and the likely variations in mode of fluid movement within them.

It is only very recently, perhaps in view of the revived interest in the anaerobic digestion process due to increased energy consciousness, that the environmental engineering community has begun to focus its attention on the process in the light of up-to-date, modern techniques, systems and knowledge. Smart and Boyko (21) note that, "while engineers ... express concern over ... a tenth of a pound difference in oxygen transferred by an aerator, somewhat more subdued reactions are reserved for the performances of digesters and their systems in general, giving the impression that the development of the process is being somewhat neglected ..... Digester mixing, heating, insulation, cleaning and gas drying are some areas where much investigative effort could be applied".

In early laboratory scale studies investigating the influence of biochemical and physical factors upon the anaerobic digestion process, Buzzell and Sawyer (23) related digesting sludge total solids and ash content to viscosity, showing large variations in viscosity with varying ash content particularly above a total solids content of 3%. These authors concluded that the effect of the viscous properties of digesting sludge on digester mixing patterns may be a limiting factor in the design and operation of high-rate digesters.

This conclusion suggests that ideally, the design of digester mixing equipment should be regarded as site specific and based upon the physical properties of the incoming raw sludge, and the digesting sludge.

3. DESCRIPTION OF EXPERIMENTAL APPROACH, PROCEDURES AND METHODS

3.1 Approach

Initial plans were to select up to a dozen two-stage digester systems, half of them gas mixed, the others mechanically mixed, to provide a good, definitive cross-sectional evaluation of the various mixing devices commonly used in Ontario. It was hoped that the study would provide:

a) *Comparison between mechanical and gas recirculation mixing methods.*

b) *Evaluation of various mixing systems within the two basic mixing methods.*

c) *Most importantly, a general, quantitative assessment of the actual mixing being achieved in these digesters.*

It quickly became apparent that a definitive, relative assessment of the efficiency of mixer types and methods was impossible for several reasons. The primary reason opposing such an approach was the general condition of the digestion systems in Ontario. In brief, where a definitive approach is made, test systems should be of the same, or similar geometry and state of repair, i.e. bottom deposits should be constant, or better still, non-existent, suggesting a very recent cleanout of the digester, and secondly, the mixing equipment should be recently overhauled and in new condition allowing fair comparisons. It was obviously impossible to find several plants which fulfilled all of these conditions. In addition, it became very apparent that study results would be even more site-specific due to the many mixer types and installation patterns extant. While these differences in themselves might be an interesting comparison, general physical and mechanical condition variations of different digesters would preclude valid comparisons of relative performances.

With these observations in mind, it was felt that the study would be regarded as, and limited to, a generalized survey of digester mixing efficiencies in the units tested with little attempt made to categorize or compare the various systems due to the high degree of site specificity in work of this nature.

It was also decided that the study would not include single-stage digestion systems, due to the peculiarities of their operation where mixing must be stopped in a multitude of differing schedules to allow supernatant discharges.

With this rationale in mind, a dozen digestion systems in Southern Ontario were tentatively selected for study. The simplified selection criteria were that the digestion systems should be in good, steady-state operation, with no major sludge feed rate fluctuations projected for the period of study, about one month for each digester. From these systems, ten were ultimately selected for study, with four being mechanically mixed, and the remainder gas mixed. Appendix 1 summarizes the mixing performance results obtained.

3.2 Testing Procedures

(i) Due to its practical simplicity, the method of Tenney and Budzin (12) was initially selected for the mixing studies. This method offers an assessment of actual hydraulic retention time as opposed to theoretical, nominal retention time. Briefly, the method consists of a two day, no-flow period, at the start of which the digester is dosed with an appropriate amount of tracer. During this initial two day period, depth profile samples are collected at

frequent intervals, every half hour to one hour, to provide an assessment of the rate of tracer distribution at varying depths, and the time required for tracer concentration homogeneity. At the end of the no-flow, two day period, raw sludge feeding is resumed and daily primary digester overflow, or transfer sludge samples taken for three to four weeks for tracer analysis. This provides a tracer response curve of the form:

$$C = C_o e^{-\frac{t}{\tau}} \qquad (A)$$

where: C = *concentration of tracer at any time,* t

C_o = *initial theoretical tracer concentration assuming total digester volume utilization*

t = *time (days)*

τ *(TAU)* = *hydraulic retention time (days)*

From this equation, the mean actual hydraulic retention time can be calculated by graphical solution of the slope of the line:

$$\ln \frac{C}{C_o} = -kt \qquad (B)$$

where $k = \frac{1}{\tau_{OBS}}$

The theoretical hydraulic retention time is given by:

$$\tau_N = \frac{V}{Q}$$

where V = *digester volume*

and Q = *substrate feed rate*

Q may also be expressed in m^3/d (gpd) digested sludge hauled, but this number is likely more difficult to measure accurately as it is invariably unmetered and is measured by truckloads, whose actual volume hauled may vary from run to run.

In the studies, fluoride, as sodium fluoride, NaF, was used as a tracer. The literature suggests that the fluoride ion is one of the few tracers suitable for the anaerobic digester environment as it is fully recoverable, non-toxic at concentrations less than 500 mg/L and non-reactive. All digesters were dosed to initial theoretical fluoride concentrations of 20-40 mg/L. Background fluoride levels were also measured prior to dosing with tracer. All subsequent results shown in the report are corrected for background fluoride concentrations.

The sodium fluoride tracer was dissolved in water and introduced in pulses to the digesters, through the scum pits. The scum pits and all lines were purged three or four times with water to ensure that all the tracer was injected with no settling, or retention in the pipeworks.

Depth profile samples were taken through digester roof sample ports during the two day, no-flow periods. After raw sludge feed resumption, transfer sludge samples were collected daily for three to four weeks and were returned to the main MOE Toronto Laboratories for fluoride analyses.

(ii) While the test method of Tenney and Budzin (12) was considered reasonably useful, its inherent incapacity to quantify substrate bypass, or short-circuit, rendered it incapable of truly representing the overall mixing performance of anaerobic digesters.

For this reason, beginning with Digester D, all subsequent mixing studies were conducted using the model and procedures outlined by Monteith and Stephenson (13). The method is a stimulus-response technique using a fluoride tracer pulse in the inlet substrate stream under steady-state flow conditions. In the studies, daily digester exit samples were taken for 3-4 weeks after dosing, for fluoride analyses. Digester exit, or transfer sludge, was also intensively sampled for several hours immediately following tracer addition to provide observation of substrate short-circuit.

In the event of substrate short-circuiting, the data were analyzed by the model (13):

$$\frac{C}{C_o} = \left[Q_1 V/Q^2/\bar{\tau}_{OBS} \right] e^{-\frac{t}{\bar{\tau}_{OBS}}} + (Q_2/Q) \quad \delta(t=0) \qquad (C)$$

where no substrate short-circuit was noted, data were analyzed by the model (13):

$$\frac{C}{C_o} = \left(\frac{V}{Va} \right) e^{-tV/Va/\bar{\tau}_{OBS}} \qquad (D)$$

where: C_o = initial theoretical tracer concentration assuming total digester volume utilization

C = tracer concentration at time, t

V = nominal digester volume

Va = actual digester mixed volume

Q = total substrate feed rate to digester

Q_1 = fraction of Q entering active mixed zone

Q_2 = fraction of Q short-circuiting

$\bar{\tau}_{OBS}$ = mean observed hydraulic retention time in actively mixed zone

δ = Dirac delta function

Digester dead space, $V_d = V-Va$, is defined as a region of the vessel which will retain sludge for periods of an order of magnitude greater than the mean retention time of the total system.

Substrate short-circuit (Q_2) is defined as that portion of the substrate passing through the digester in a time which is a small fraction of the mean retention time of the overall substrate. For all practical purposes, this low retention time portion of substrate can be considered as short-circuiting the digestion process.

The Dirac delta function (δ) is the mathematical expression of an instantaneous pulse or injection of tracer to the digester. With relation to the long retention times associated with anaerobic digesters, the tracer addition can, for practical purposes, be considered instantaneous.

The model of Monteith and Stephenson (13) is derived from that of Cholette and Cloutier (17) where dead space is considered to be completely stagnant. While this is not completely true, it is a fair assumption, as in most cases sludge which remains in a digester for two or more times the mean residence time can, with negligible error, be considered stagnant.

The model of Adler and Hovorka (28) provided a consideration of dead space as a second perfectly mixed region which interchanges fluid slowly with the active flow region by cross-flow. While this model is perhaps more representative of the anaerobic digestion process, as a dead space will transfer mass by at least molecular diffusion, the mathematical solutions are considerably more complicated than the Cholette & Cloutier (17) model. In any event, as the reactions or mass transfer in an anaerobic digester due to turbulent mixing likely occur infinitely more rapidly than by molecular diffusion, and as some substrate passes from the digester inlet to the outlet in much less time than the mean digestion retention time, the approximations of the Cholette and Cloutier (17) model are considered valid.

3.3 Fluoride Tracer Analyses

Digester sludge samples containing fluoride tracer were initially returned to the Main MOE Laboratories for fluoride analyses. Due to the nature of anaerobic sludge, the samples were centrifuged and filtered before submission for analyses by the Alizarin Visual Method as outlined in Standard Methods for the Examination of Water and Wastewater (24).

During the studies conducted on Digesters A, B, and C, however, it became apparent that the analytical method was inaccurate, producing results about 50% lower than were stoichiometrically possible. In brief, at all of the three above sites, initial fluoride $^{C}/C_{o}$ ratios were much less than the ideal unity, where, if anything, they should have been unity or higher. Checks of the method using stock fluoride solutions showed over 99% fluoride recovery. Previous studies conducted by the MOE Laboratories Branch had indicated equally good fluoride recovery from digested sludge samples. It was therefore

not clear whether in the present case, the abysmally poor fluoride recoveries were due to interference by trivalent metals such as Al^{+++} and Fe^{+++}, both of which are commonly used in the Ontario phosphorus removal program, or by physical adsorption on the solid sludge phase, causing the fluoride reduction by the process of centrifugation and filtration of these solids noted earlier.

Subsequently, the Alizarin Method was replaced by the specific ion electrode technique which obviated the necessity to filter the samples.

Accordingly, analyses were conducted using a fluoride ion selective probe used with an Orion expanded scale pH/mV meter. The analytical method used was that described by McQuaker (22) and modified by Turner and Engler (29). This method was found to be fairly accurate by laboratory studies. Appendix 2 shows results obtained on sludge samples containing known amounts of fluoride.

A comparison of the Alizarin and Probe methods showed that the probe was consistently higher than the colorimetric method by a factor of approximately 2. This held independently of fluoride concentration suggesting that the low results obtained from the three initial digester studies would still be valid in determining the mean actual hydraulic residence time, as the slope of the tracer washout line would be little affected even though the magnitudes of the concentrations were at variance with the actual values. For this reason, it was felt reasonably valid to assign the measured initial fluoride concentration the value of C_o *in drawing dimensionless graphs and subsequent calculations.*

The experiences briefly described here on the analysis of fluoride ion in digested sludge may be of note or caution to future researchers. While fluoride ion seems indeed to be non-reactive in the anaerobic digestion environment, its analysis can, apparently, be influenced by other ions present to a degree where its use might be regarded as site-specific and subject to replacement by other tracers such as radioisotopes.

4. RESULTS AND COMMENTS ON INDIVIDUAL DIGESTER MIXING STUDIES

4.1 Primary Digester A

The pertinent design and operating data on primary digester A at the time of the study were:

diameter	:	12.2 m	(40')
liquid sidewall depth	:	6.5 m	(21')
bottom cone height	:	15 cm	(0.5')
volume	:	754 m^3	(165,919 gal)
sludge feed rate (Q)*	:	16 m^3/d	(3,600 gpd)
nominal hydraulic retention time (τ_N)*	:	46 days	

Digester mixing is applied by gas recirculation through a circular pipe 3.7 m (12') in diameter concentrically mounted on the digester floor.

Mixer data:

Blower nameplate power	:	2.24 kw (3 HP)
Blower rate	:	23.6 dm/s (50 cfm)
Blower pressure	:	103 kPag (15 psig)
Specific Gas Recirculation rate	:	31.3 $dm^3/s/1000\ m^3$ (1.88 $cfm/1000\ ft^3$)
Specific Applied Nameplate Power	:	2.97 $kW/1000\ m^3$ (0.11 $HP/1000\ ft^3$)

Initially, raw sludge feed to the digester was halted and the unit pulse dosed to a theoretical fluoride concentration of 26.5 mg/L. Sludge samples were then taken at half hour intervals and at 1.5 m (5') depth increments through two roof sample ports for 9.5 h following tracer addition. The two roof sample ports are each 10' from the roof centre and 180° apart.

* During the study, it was discovered that the raw sludge and recirculating sludge pumps' water seals ran full-time, admitting rather large quantities of water to the primary digester. The total volume of combined raw sludge and water feed to the digester was estimated as 45.5 m^3/d (10,000 gpd) from water line size and pressure calculations and from past digested sludge haulage schedules. On the basis of this revised, actual digester feed rate, the nominal hydraulic retention time was seen to be 17 days as opposed to 46 days shown above. Since the study, the pump seals have been changed to mechanical packings.

Sampling was continued next day from 24 to 33 hours after dosing. The samples were then filtered and returned to the Toronto Laboratory for fluoride analyses. The results of this portion of the study are shown on Figures 1 and 2. Note that only the results for the surface and 4.6 m (15') off-bottom sample points are drawn. Other samples were taken at the bottom, 1.5 m (5') off-bottom and 3 m (10') off-bottom in every case, but as the results of these fall on or within the lines drawn, only these two are drawn in the figures for clarity. In short, the drawn curves show the maximum spread of results.

Perhaps the most interesting feature of these results was the failure to achieve the theoretical fluoride concentration of 26.5 mg/L. The highest concentration attained was 17.5 mg/L (Figure 1 West sample port, 4.6 m (15'), at 7 hours after dosing. Another interesting feature of the curves was the rapidity with which the tracer dispersed at all tank depths. The curves suggest that homogeneity of tracer concentration was achieved in approximately 4-6 hours, indicating perhaps surprisingly good mixing ability.

Later in the study, the high flow of pump seal water to the digester was discovered and the anomalies noted from Figures 1 and 2 were, at the time, ascribed to this fault.

In completion of this portion of the study, raw sludge feed to the primary digester was resumed and the transfer sludge sampled daily for fluoride analyses to provide a tracer decay curve. Sampling was continued for twenty-five days.

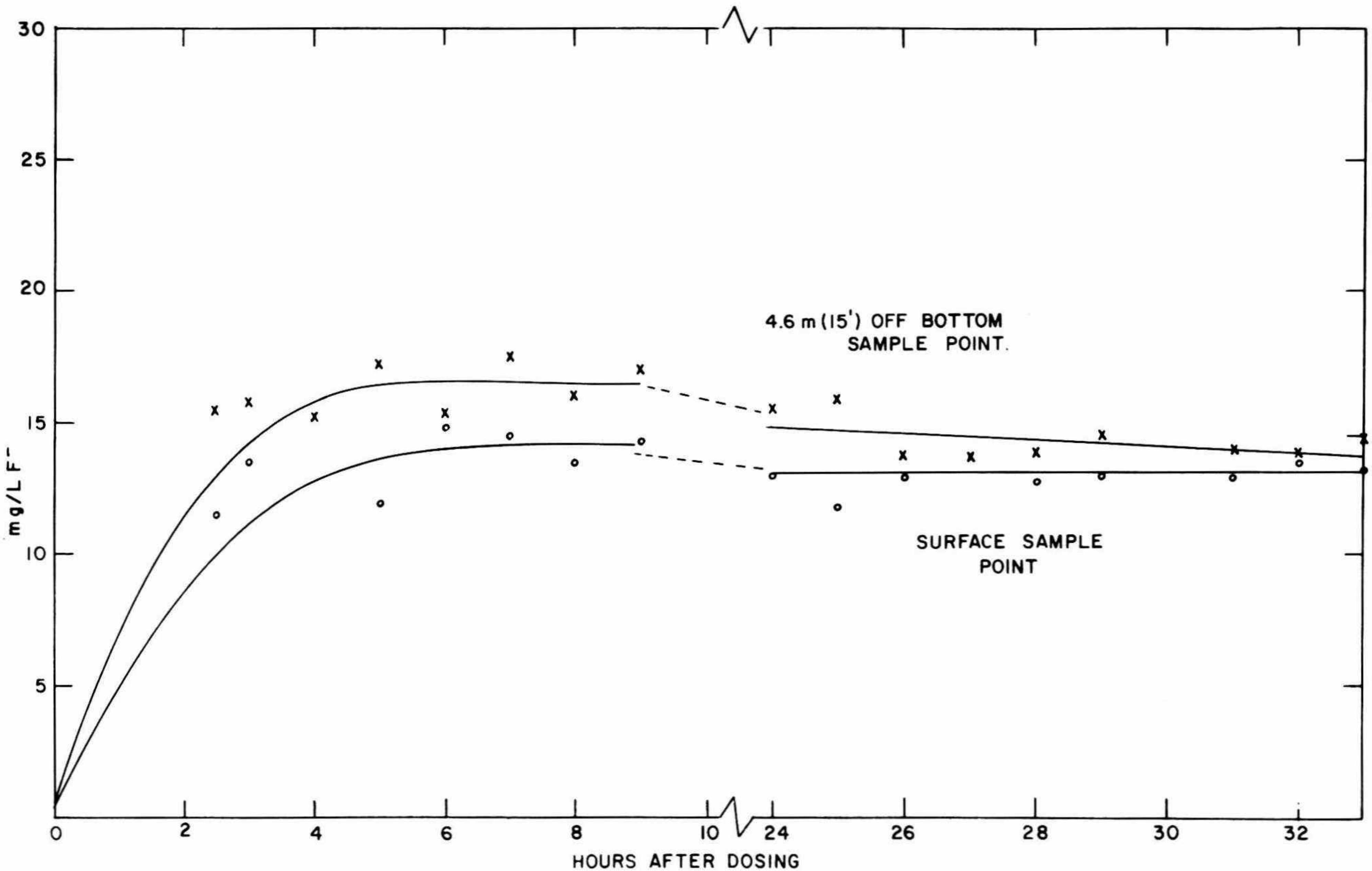

FIGURE 1 DIGESTER 'A' DEPTH PROFILE — WEST SAMPLE PORT.

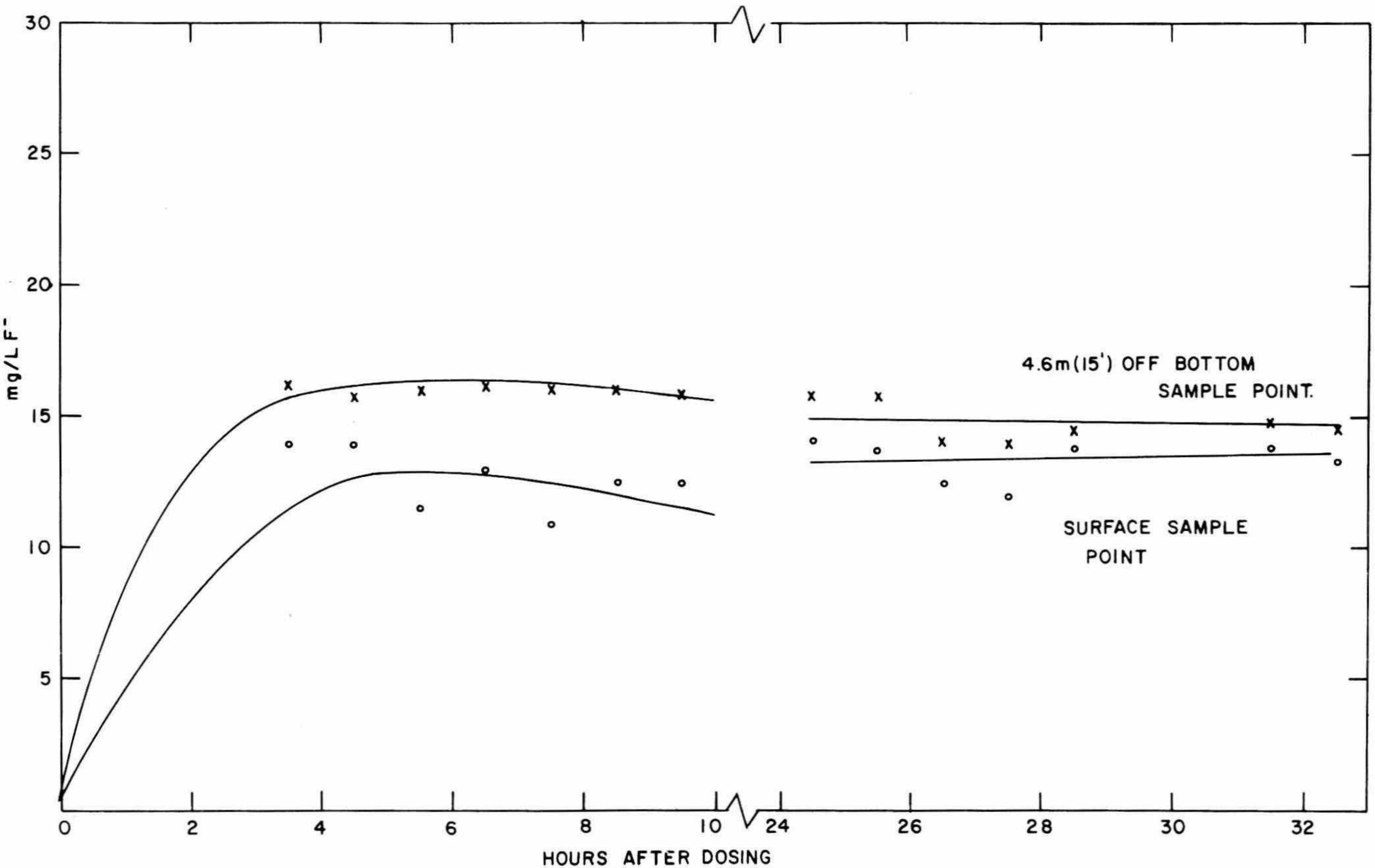

FIGURE 2 DIGESTER 'A' DEPTH PROFILE — EAST SAMPLING PORT.

Figure 3 shows a dimensionless plot of tracer decay and time. From the slope of the line, the mean actual hydraulic retention time was calculated to be 11 days; considerably less than the theoretical 17 days showing poor digester volume utilization.

It was noted earlier, that no-flow conditions analyses on samples taken from both roof sample ports showed rather good mixing patterns suggesting good volume utilization, while the second part of the testwork, the tracer decay studies, clearly indicated the opposite case to be true. This apparent contradiction in results from both parts of the primary digester A retention time study can most likely be explained by the physical, or geometrical aspects of the digester.

The explanation for these differences is probably related to the position of the sample ports on the roof. As seen earlier, primary digester A has an inside diameter of 12.2 m (40') with the sample ports each being 3 m (10') from the walls. In short, the two sample ports lie in the likely area of greatest mixing intensity and the analyses on samples from these positions reflected the mixing patterns in a relatively small, isolated portion of the digester. Conversely, the tracer decay curve under steady-state flow conditions reflected a consideration of the <u>total</u> tank volume distribution and is thus regarded as being a much more

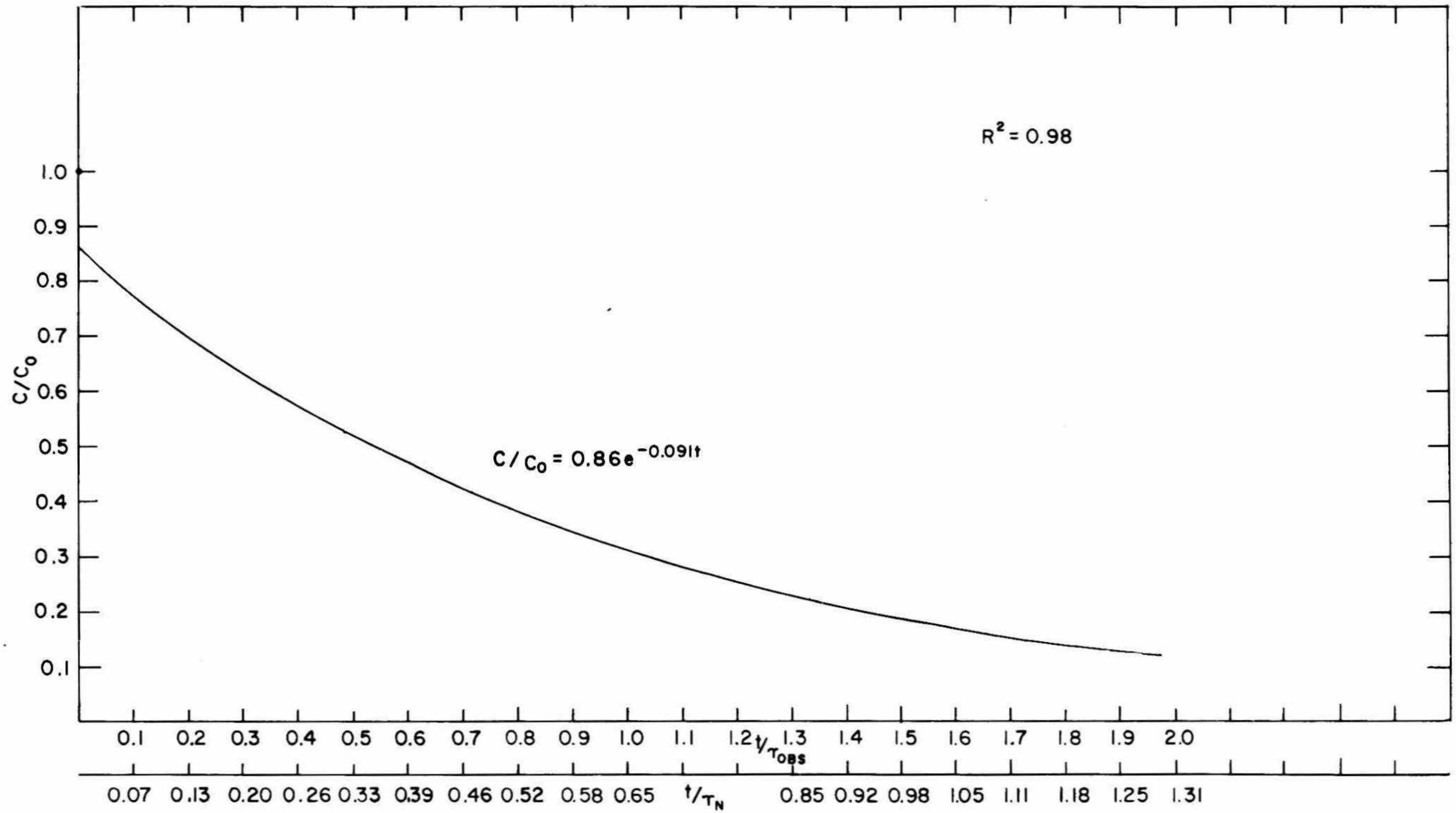

FIGURE 3 PRIMARY DIGESTER 'A' TRACER DECAY CURVE.

realistic appraisal of mixing as measured by mean observed hydraulic retention time. It is likely that little mixing is applied to the outer portions of the digester and expected that solids deposition will occur in that region. Unfortunately, in this, and most other digesters, there is no provision for depth profile sampling in the area close to the walls to confirm these conclusions. It might also be noted that digester A transfer sludge was very poorly digested, being brown and displaying other raw sludge characteristics.

4.2 Primary Digester B

Primary digester B is the first-stage unit of a two stage digestion system.

Design and Operating Data

diameter	:	15.4 m	(50')
liquid sidewall depth	:	6.1 m	(20')
bottom cone height	:	1.9 m	(6.25')
volume	:	1229 m^3	(270,390 gal)
sludge feed rate (Q)	:	32.7 m^3/d	(7,200 gpd)
nominal hydraulic retention time (τ_N)	:	37.6 days	

Digester mixing is accomplished by a single mechanical mixer.

Mixer Data

Type	:	Walker
Nameplate Power	:	7.46 kw (10 HP)
Propellor	:	4 blade; 61 cm (24") diameter turning at 294 rpm. Located 61 cm (24") below surface and served by a 76 cm (30") diameter, 4 m (13') long draft tube. Flow direction reversible.
Specific Applied Nameplate Power	:	6.07 kw/1000 m^3 (0.23 HP/1000 ft^3)

Digester "B" is equipped with a single roof sample port located 3 m (10') from the centrally mounted mixer.

As in the previous study, sludge feed to primary digester B was halted for two days after dosing with fluoride tracer, and depth profile sampling conducted at approximately 1.5 m (5') intervals from the bottom of the digester to the surface for a total of six sampling depths. As before, the tracer was introduced to the system via the scum pit in a quantity calculated to dose this unit to a theoretical 32.5 mg/L as fluoride.

The results of the depth profile sampling at no-flow conditions are shown in Figure 4.

The two curves on Figure 4 show the results from the 1.5 m and 4.6 m (5' and 15') samples as measured from the digester floor. All other fluoride concentration results fall close on, or within these lines. As before, the curves show the general range of results.

Interestingly, when compared with the results from digester A seen on Figures 1 and 2, the digester B curves show a much greater spread of values and a lesser attainment of steady-state fluoride concentrations even after 33 hours mixing time. This would tend to suggest that digester B achieved a lower mixing intensity than unit A although, again, the rate of distribution of the tracer seemed generally quite good.

Here also, the measured level of fluoride failed by a large margin to meet the theoretical dosage of 32.5 mg/L. The highest fluoride concentration observed at any time at any sampling position was 23 mg/L. In this case, this anomaly could not be attributed to a flow throughput from any source as great care was taken to check that the system was indeed sealed. The apparent loss of fluoride was therefore unexplainable at this time.

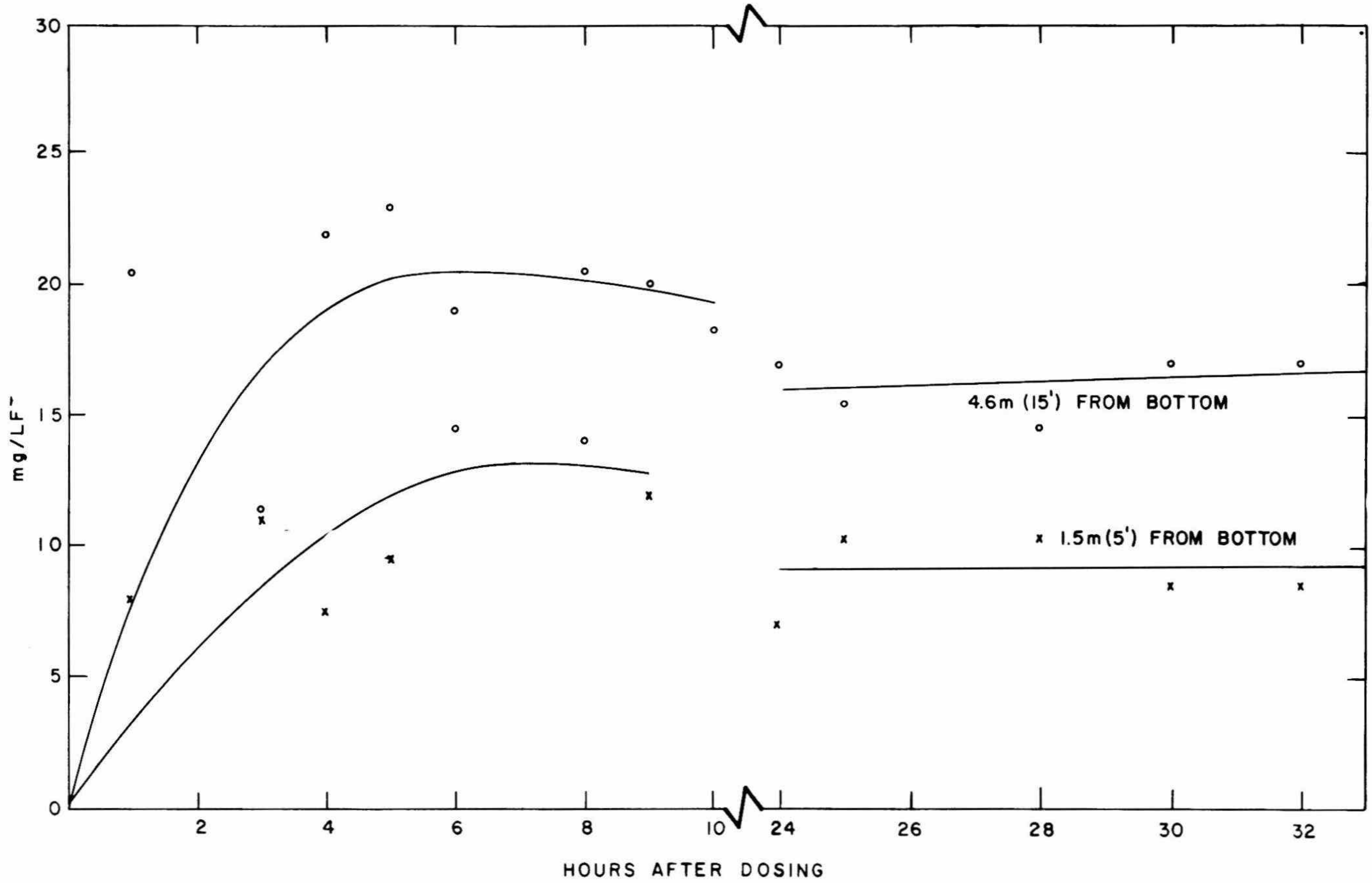

FIGURE 4 DIGESTER 'B' DEPTH PROFILE SAMPLES

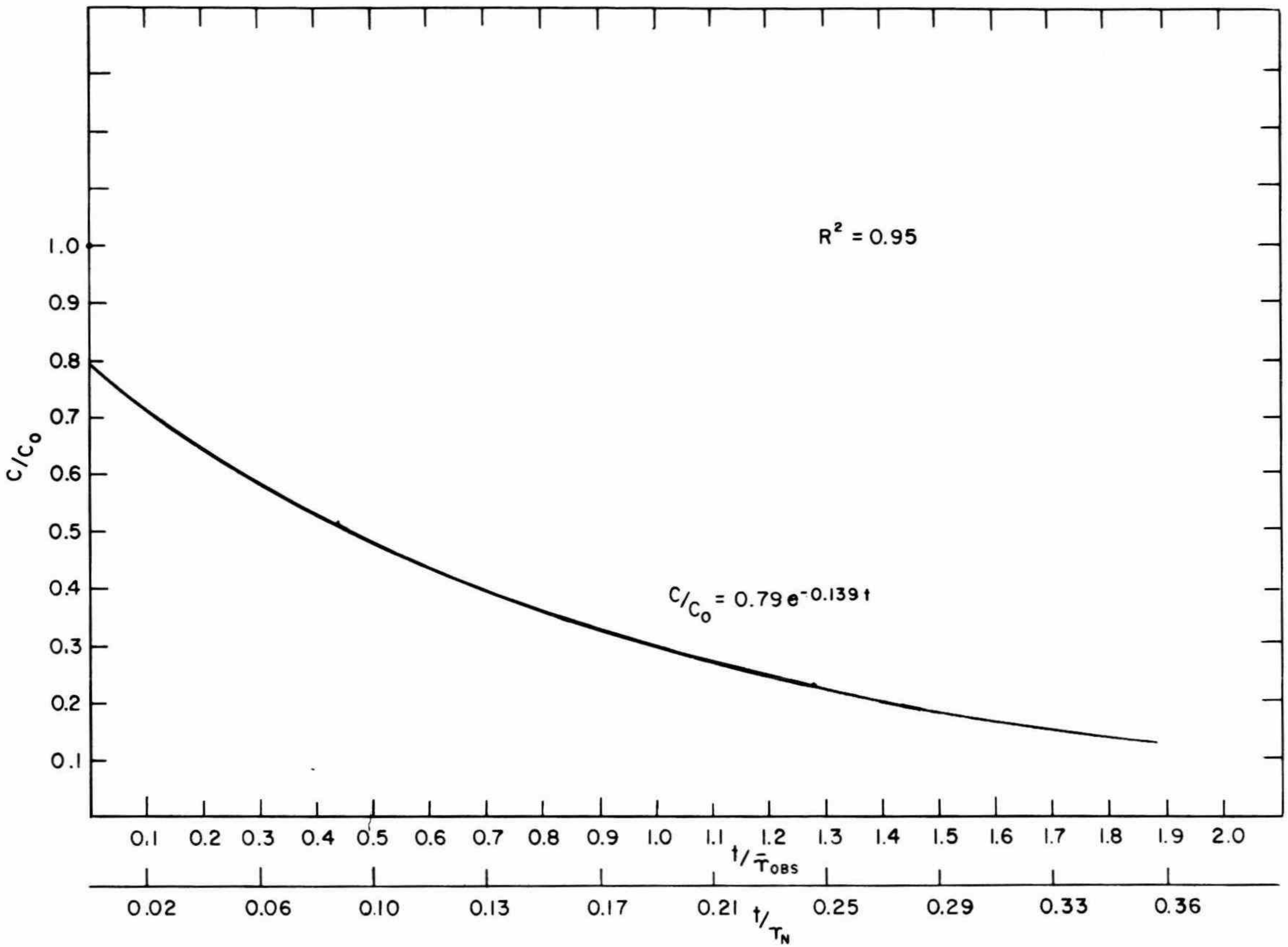

FIGURE 5. PRIMARY DIGESTER 'B' TRACER DECAY CURVE.

After the two day no-flow period, raw sludge pumpings were resumed and the overflow from the primary digester sampled daily for seventeen days. Figure 5 shows the dimensionless tracer decay curve. The actual, mean hydraulic retention time was calculated from the slope of the line as 7.2 days. Compared with the theoretical hydraulic retention time of 37.6 days, the observed mean retention time of 7.2 days was extremely low.

In this case again, it was felt that the fairly good results obtained from the first part of the study, under no-flow conditions and depicted in Figure 4, were somewhat misleading due to the positioning of the sampling port in the likely zone of greatest mixing influence close to the mixer. Interestingly, the transfer sludge at this plant, however, was fairly black in colour, and showed the characteristics of a reasonably well digested sludge.

4.3 Primary Digester C

Digester C serves as the primary unit in a two stage system and is mechanically mixed.

Design and Operating Data

diameter	:	24.4 m (80')
liquid sidewall depth	:	6.6 m (21.5')
bottom cone height	:	1.0 m (3')
volume	:	3532 m^3 (776,880 gal)
sludge feed rate (Q)	:	159 m^3/d (35,000 gpd)
nominal hydraulic retention time (τ_N)	:	22 days

Mixer Data

Type	:	*Dorr-Oliver-Long (3 units)*
Nameplate Power	:	*5.6 kw (7.5 HP) each*
Specific Applied Nameplate Power	:	*4.75 kw/1000 m^3 (0.18 HP/1000 ft^3)*

The three mixers are served by draft tubes, and are spaced 120^o apart and located about 7.5 m (25') from the centre of the roof. The roof sample port is located about 4.6 m (15') from the sidewall and 3.7 m (12') from a mixer.

Results of the no-flow depth profile sampling program are shown on Figure 6. The data points drawn are the averages of five sample depths. Analytical results on the various depths were so close as to be regarded practically as one. This portion of the testwork again indicated rather good, rapid dispersion of the tracer. However, as in the previous testwork, the fluoride concentration attained was much lower than the calculated dosage of 20 mg/L. Again, at this time, this was inexplicable in terms of the test facility or procedure, as all precautionary measures were taken to ensure no-flow conditions and that all the fluoride tracer was, indeed, discharged from the scum pit to the primary digester. In every case, the scum pits and sludge feed pipes were purged into the primary digesters using at least three times their volume of water.

It was thus clearly apparent that the alizarin method for fluoride analysis in digested sludge was highly suspect notwithstanding the findings of earlier researchers. As noted earlier, all subsequent fluoride analyses were conducted using a specific ion electrode.

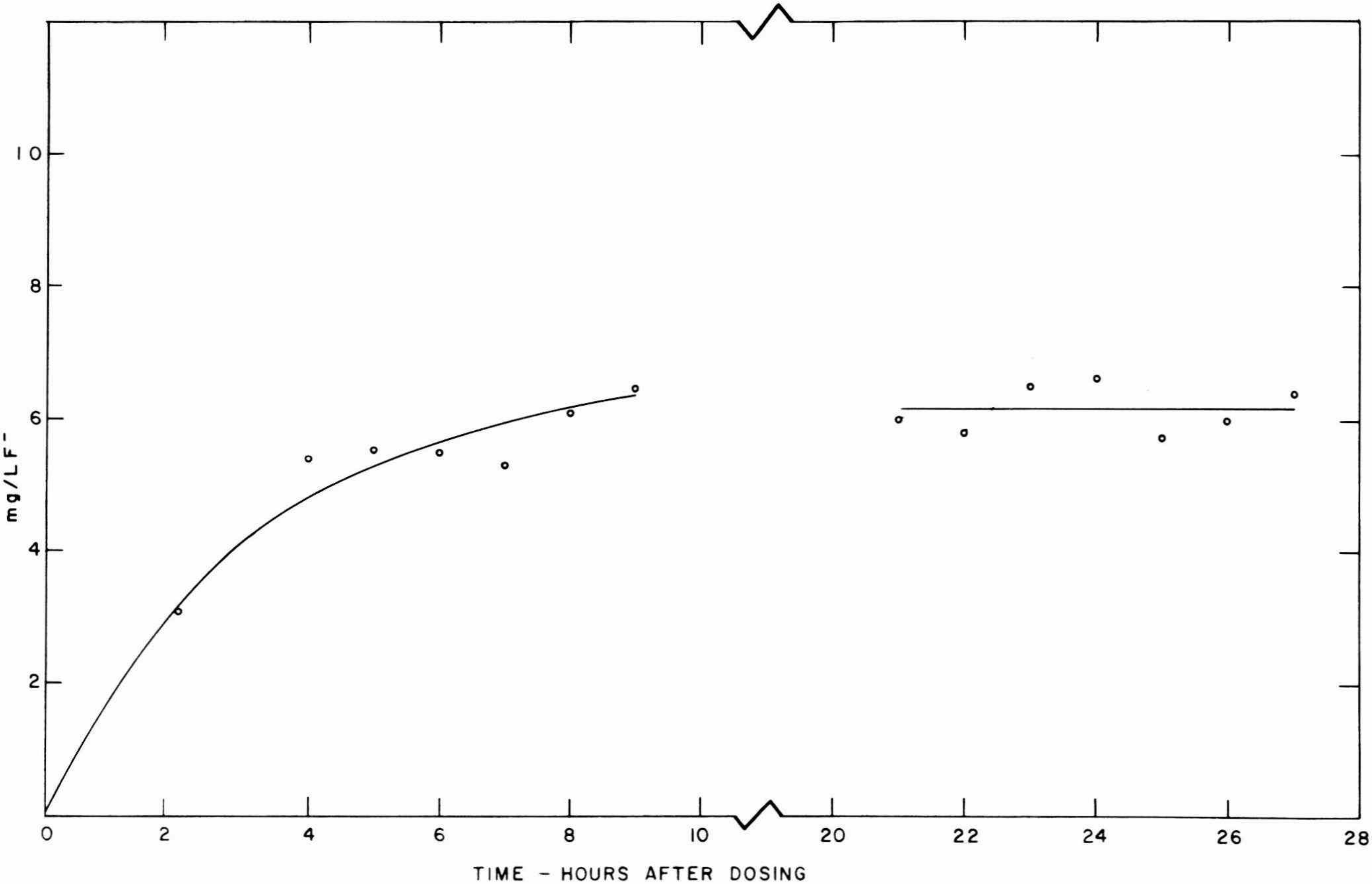

FIGURE 6 DIGESTER 'C' DEPTH PROFILE SAMPLES.

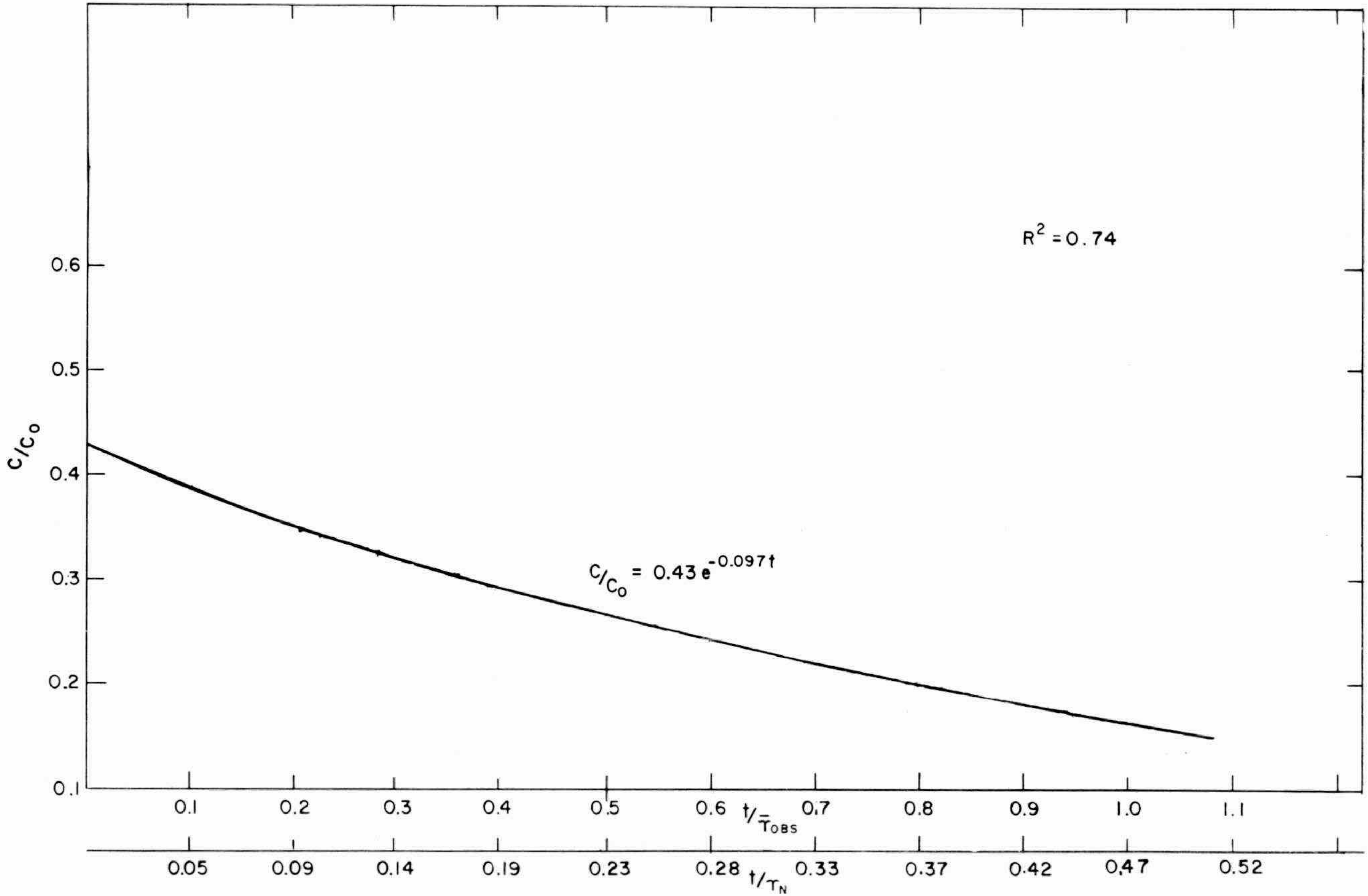

FIGURE 7 PRIMARY DIGESTER 'C' TRACER DECAY CURVE.

Following the completion of the no-flow depth profile sampling survey, sludge substrate was re-introduced to the primary digester and the transfer sludge monitored as before to provide a tracer decay curve. These data are plotted dimensionlessly in Figure 7.

From the slope of the line, the mean primary digester hydraulic retention time $\bar{\tau}_{OBS}$, was calculated to be 10.3 days.

The observed primary digester mean hydraulic retention time of 10.3 days is 47% of the theoretical retention time showing very poor digester volume utilization.

Comments previously made on the positioning of roof sampling ports on digesters A and B also apply here as evidenced by a comparison of Figures 6 and 7.

Interestingly, subsequent to the testwork, WPCP staff removed and inspected the three mixers.

On one unit, the propellor was completely corroded with only the drive shaft remaining. The other two units were in slightly better condition with some portions of their propellors remaining. At the present time, all three units are being reconditioned. This would in great part explain the poor mixing seen in primary digester C.

4.4 Primary Digester D

Digester D is the primary unit of a two stage digestion system and is mixed by gas recirculation. It is unusual in having a rather large liquid sidewall depth as seen in the data.

Design and Operating Data

diameter	: 15.2 m (50')
liquid sidewall depth	: 11.9 m (39')
bottom cone height	: 1.8 m (6')
volume	: 2282 m^3 (502,089 gal)
sludge feed rate (Q)	: 81 m^3/d (17,840 gpd)
nominal hydraulic retention time (τ_N)	: 28 days

Mixer Data

Type	: Aero-Hydraulic (5 units)
Gas Blower	: C.P. Lammert 1.5 kw (2 HP)
Blower Rate	: 10.4 dm^3/s (22 cfm)
Blower Pressure	: 120.7 kPag (17.5 psig)
Specific Gas Recirculation Rate	: 4.6 dm^3/s/1000 m^3 (0.27 cfm/1000 ft^3)
Specific Applied Nameplate Power	: 0.65 kw/1000 m^3 (0.02 HP/1000 ft^3)

As noted previously, the method of Stevenson (13) after Choulette and Cloutier (17) and Levenspiel (18) was used to assess the mixing performance of this, and all subsequent digesters.

This method consists of dosing the digester with a pulse of tracer during steady- state sludge pumping schedules, followed by an immediate, intensive transfer sludge sampling program of half-hourly samples for the first 7-8 hours, followed by single daily samples for 20-30 days. It was felt that in the event of short-circuiting of substrate, this effect would be seen in the first few hours following tracer addition. The subsequent daily samples for the remainder of the test program provided data to quantify dead space, actual hydraulic retention time and short-circuit.

The intensive, half-hourly sampling program run for seven hours immediately following dosing primary digester D with fluoride tracer showed a large short-circuit effect beginning at 30 minutes after dosing, peaking at 3 hours and completed by the seventh hour.

This is displayed in Figure 8. As the digester had been dosed to a theoretical fluoride concentration, C_o, of 30 mg/L, the observed short-circuit was of rather massive proportions, reaching a maximum fluoride concentration of 1780 mg/L ($^C/C_o = 59$). A mass balance showed that 18 kg (39.5 lbs) of fluoride, or 26.2% of the initial fluoride added, had been removed in the first 7 hours of the study.

Figure 9 shows the best fit curve of tracer decay over a twenty-day period for Digester D. From the slope of the line, the mean actual hydraulic retention time, $\bar{\tau}_{OBS}$, was calculated to be 22.8 days. The y intercept of the curve on Figure 9 provided a value for the expression, $(Q_1V/Q^2)/\bar{\tau}_{OBS}$ in equation (C):

$$\frac{C}{C_o} = \left[Q_1V/Q^2/\bar{\tau}_{OBS}\right] e^{-\frac{t}{\bar{\tau}_{OBS}}} + \frac{Q_2}{Q} \quad \delta(t = 0)$$

i.e. $\left[Q_1V/Q^2/\bar{\tau}_{OBS}\right] = 0.696$

As V, 2282 m^3 (502,089 gal), Q, 81 m^3/d (17,840 gpd) and $\bar{\tau}_{OBS}$, 22.8 days were known, Q_1 was calculated as shown:

$$Q_1 = \frac{0.696 \times 22.8 \times 81^2}{2282} = 45.62 \ m^3/d$$
(10,058 gpd)

therefore: $\frac{Q_1}{Q} = \frac{45.62}{81} = 0.56$ (fraction of substrate entering actively mixed zone)

therefore: $\frac{Q_2}{Q} = 1 - 0.56 = 0.44$ (fraction of substrate short-circuiting)

$$\frac{Va}{V} = \frac{Q_1 \times \bar{\tau}_{OBS}}{V} = \frac{45.62 \times 22.8}{2282}$$

$= 0.46$ (fraction of digestion actively mixed)

therefore: $\frac{Vd}{V} = 1 - 0.46 = 0.54$ (fraction of digester unmixed)

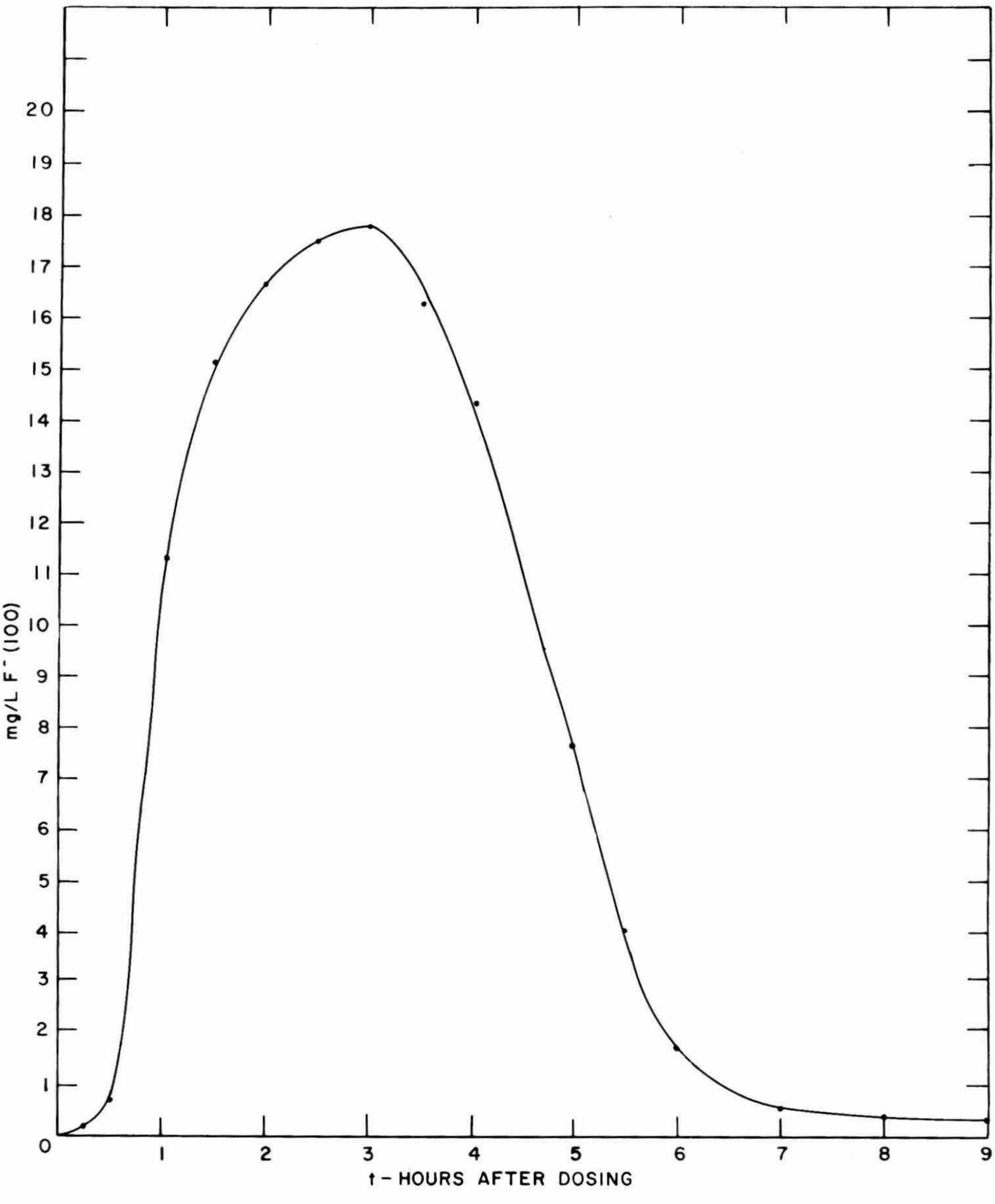

FIGURE 8 FLUORIDE TRACER SHORT CIRCUIT IN PRIMARY DIGESTER 'D'.

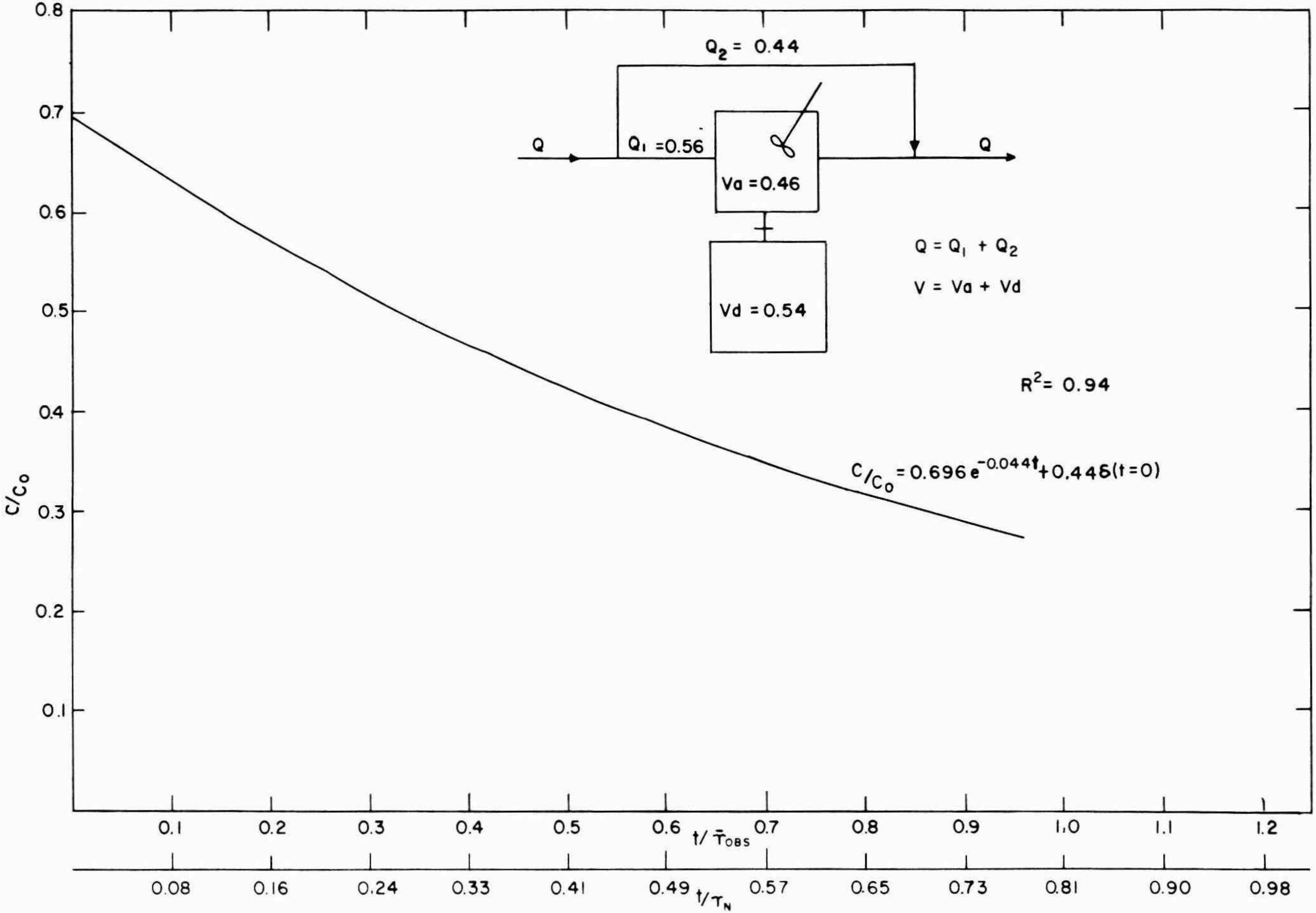

FIGURE 9 PRIMARY DIGESTER 'D' TRACER DECAY CURVES.

The calculations show that a large fraction of the substrate, 56%, was short-circuiting directly to the secondary digester and that only 46% of the primary digester volume is actively mixed. These numbers were subjectively substantiated by the appearance and odour of the transfer sludge which more nearly characterized raw sludge, indicating incomplete digestion.

4.5 Primary Digester E

Digester E is the first stage unit of a two-stage digester system and is mechanically mixed.

Design and Operating Data

diameter	: 15.2 m	(50')
liquid sidewall depth	: 6.1 m	(20')
bottom cone height	: 1.0 m	(3')
volume	: 1137 m^3	(250,000 gal)
sludge feed rate (Q)	: 118 m^3/d	(26,000 gpd)
nominal hydraulic retention time (τ_N)	: 10 days	

Mixer Data

Type	: Eimco 3.7 kw (5 HP) mechanical - 2 units
Specific applied nameplate power	: 6.6 kw/1000 m^3 (0.25 HP/1000 ft^3)

Both mixing units are served by draft tubes.

The tracer was pulse dosed to the digester to a theoretical fluoride concentration of 35.0 mg/L.

Intensive transfer sludge sampling for several hours following tracer addition showed no immediate evidence of substrate short-circuiting. Subsequent daily sampling for a period slightly exceeding one theoretical hydraulic retention period yielded the

tracer washout data shown on Figure 10. This shows a dimensionless best fit plot of concentration, $^{C}/C_{o}$ against time, $t/\bar{\tau}_{N}$ and $t/\bar{\tau}_{OBS}$, and corroborates the absence of short-circuit. The data were, therefore, analyzed by equation (D):

$$\frac{C}{C_o} = \left(\frac{V}{Va}\right) e^{-tV/Va/\bar{\tau}_{OBS}}$$

where the term V/Va was found from the y intercept of the curve in Figure 10.

$$\text{i.e.:} \quad \frac{V}{Va} = 1.11$$

$$\text{therefore:} \quad \frac{Va}{V} = 0.9 \text{ (fraction of digester actively mixed)}$$

$$\text{thus:} \quad \frac{Vd}{V} = 1 - 0.9 = 0.1 \text{ (fraction of dead space)}$$

The resulting actual mean hydraulic residence time is therefore:

$$\frac{V \times 0.9}{Q} = \frac{1137 \times 0.9}{118}$$

$$= 8.7 \text{ days}$$

Primary digester E thus proved to be by far the most efficiently mixed unit seen during the testwork so far.

It is interesting that although the hydraulic retention time of this unit was low at 9 days, a good degree of sludge stabilization was being obtained as evidenced by analysis and also by the jet black appearance and tarry odour of the transfer sludge, both of which are excellent subjective indicators of digester performance. It might be noted, however, that the staff of this WPCP maintain an unusually careful monitoring program on the digestion process. Also noteworthy, is the fact that digester E was an old unit in very poor physical condition at the time the studies were conducted, and, in fact, at the time of writing has been condemned and is due to be replaced by a new digester.

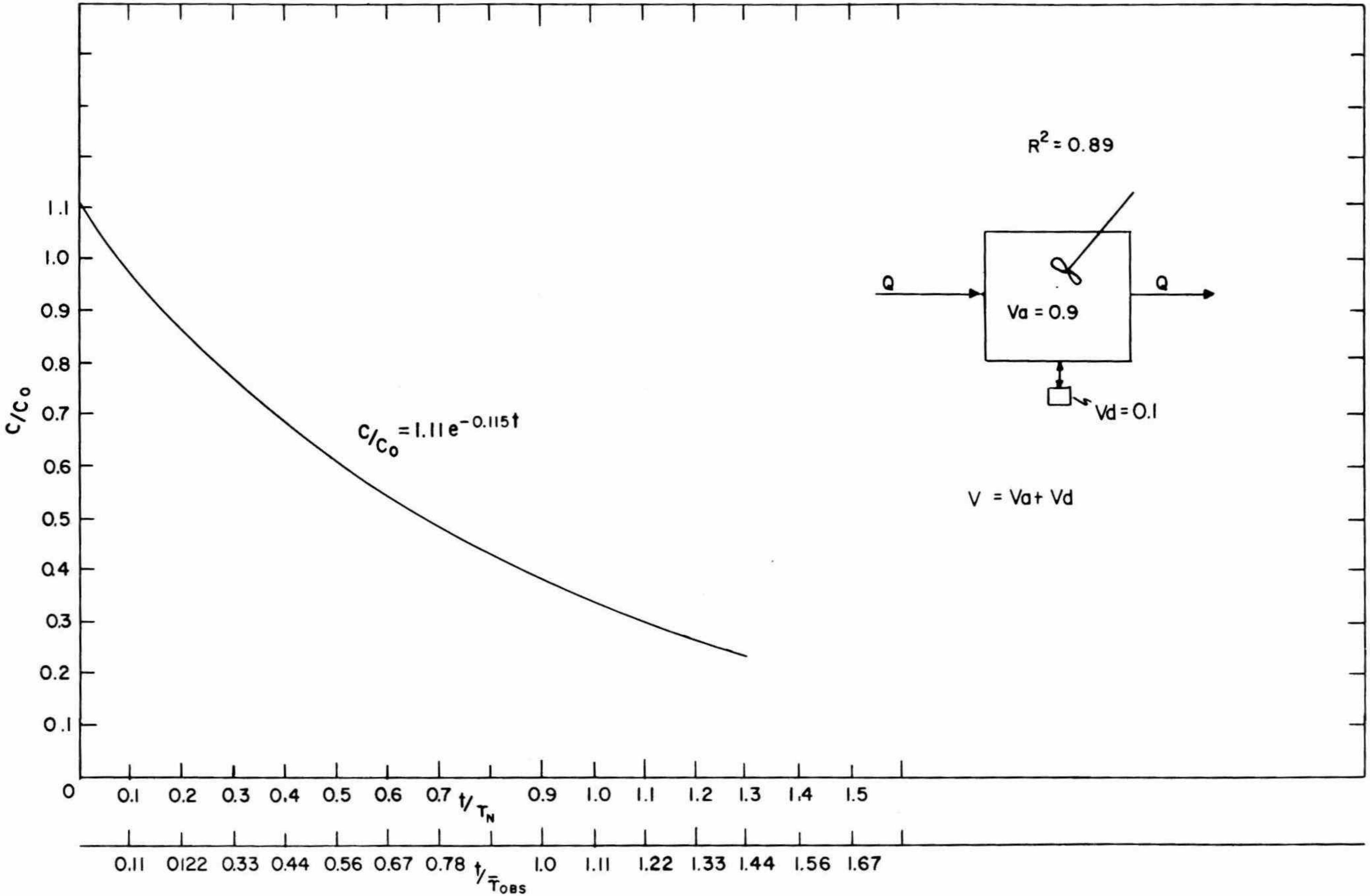

FIGURE 10 PRIMARY DIGESTER 'E' TRACER DECAY CURVES (BEST FIT).

4.6 Primary Digester F

Primary digester F is one of two new units constructed under a recent plant expansion program and offered an excellent opportunity to study the mixing efficiency of a clean, new system. Both primary digesters at this WPCP are identical and the results will apply to both units.

Design and Operating Data

diameter	:	33.5 m (110')
liquid sidewall depth	:	7.6 m (25')
bottom cone height	:	3.2 m (10.5')
sludge feed rate (Q)	:	170 m^3/d (37,413 gpd)
volume	:	7679 m^3 (1,689,213 gal)
nominal hydraulic retention time (τ_N)	:	45 days

Mixer Data

type	:	Carter/Aero Hydraulic gas recirculation Model HO-91300 (six units)
blower	:	two units, 8.95 kw (12 HP) total
specific applied power	:	1.17 kw/1000 m^3 (0.04 HP/1000 ft^3)

As installed, the six mixing units were designed to operate individually and sequentially in a rotating pattern. However, difficulties were encountered with this operational mode and the system was modified to allow simultaneous full-time operation of all six units using both blowers. The mixers are novel in that they also supply heat to the digester contents via hot water jackets.

The digester was pulse dosed with tracer to a theoretical fluoride concentration (C_o) of 26.8 mg/L and intensive, half-hourly sampling of transfer sludge initiated immediately and continued for 7.5 hours after dosing. Figure 11 shows the results obtained during this time.

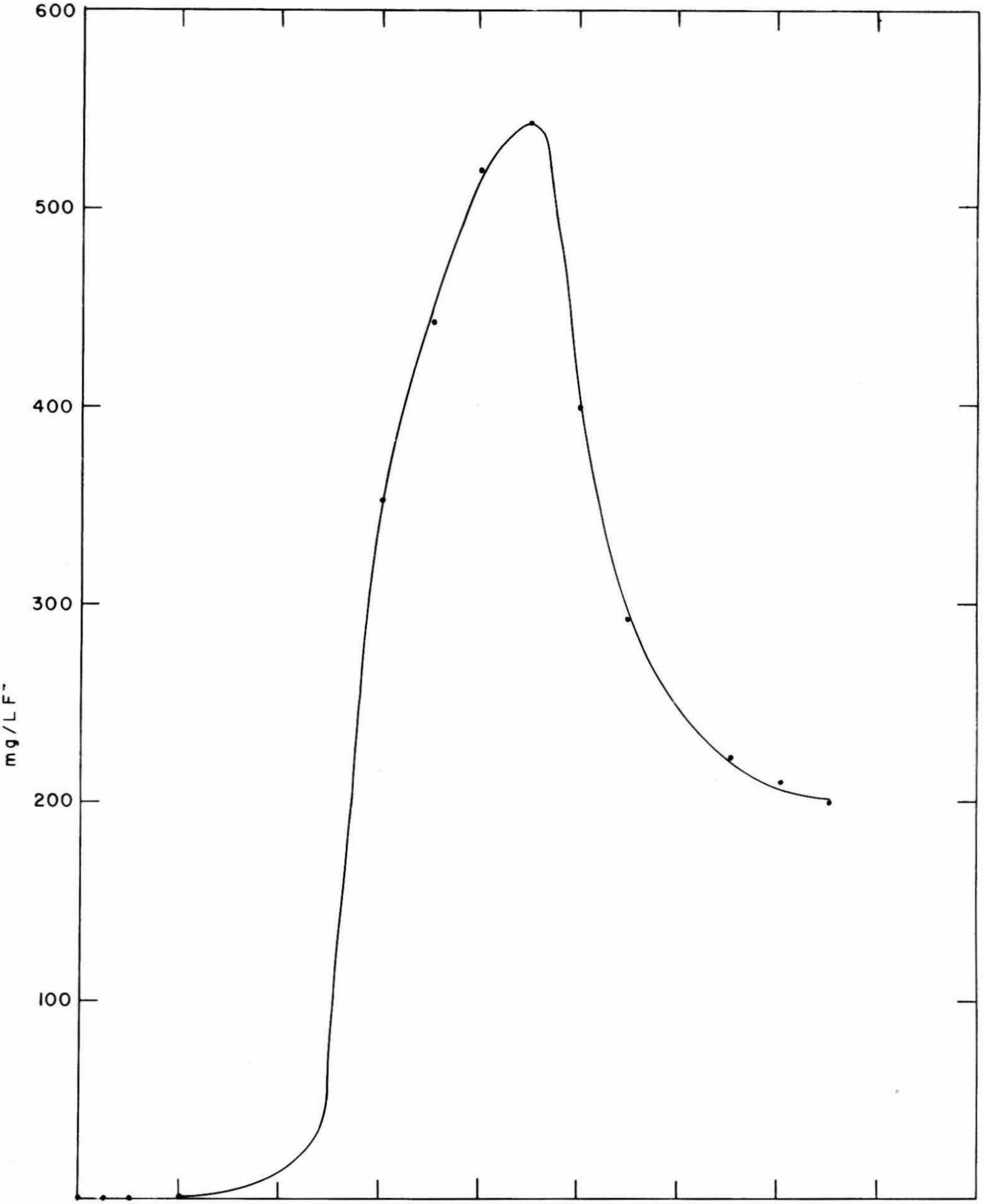

FIGURE 11 PRIMARY DIGESTER 'F' FLUORIDE TRACER SHORT CIRCUIT.

It shows that a short-circuit began soon after the digester was dosed with the tracer and continued for some time. The maximum fluoride concentration seen was in the order of 540 mg/L (C/C_o = 21). Also indicating substrate short-circuiting was the general appearance of the transfer sludge. This was brown with an obnoxious odour reminiscent of raw sludge. Interestingly, while the digester temperature probe indicated a temperature of 35°C (95°F), the transfer sludge, discharged through a pipe in the bottom of the cone, was cold to the touch, being around 10-13°C (50-55°F); again implying rather rapid, large-scale short-circuiting of incoming raw sludge substrate.

Subsequently, daily samples of the transfer sludge were taken for 20 days after tracer addition. The results are shown as a best fit curve on Figure 12 with the dimensionless concentration C/C_o being plotted against time. The slope of the line gave the mean actual hydraulic residence time as 17.9 days.

From Figure 12, the expression, $\left[Q_1 \; V/Q^2/\bar{\tau}_{OBS} \right]$ of equation (C) was evaluated by the y intercept as 0.705. As V, Q and $\bar{\tau}_{OBS}$ were know, Q_1, the volume of substrate entering the actively mixed digester zone was calculated by:

$$Q_1 = \frac{0.705\ (170^2 \ \ x\ 17.9)}{7679} = 47.49\ m^3/d$$

$$\text{therefore:} \quad \frac{Q_1}{Q} = \frac{47.49}{170} = 0.28 \quad \text{(fraction of substrate entering actively mixed zone)}$$

$$\text{and:} \quad \frac{Q_2}{Q} = 1 - 0.28 = 0.72 \quad \text{(fraction of substrate short-circuiting)}$$

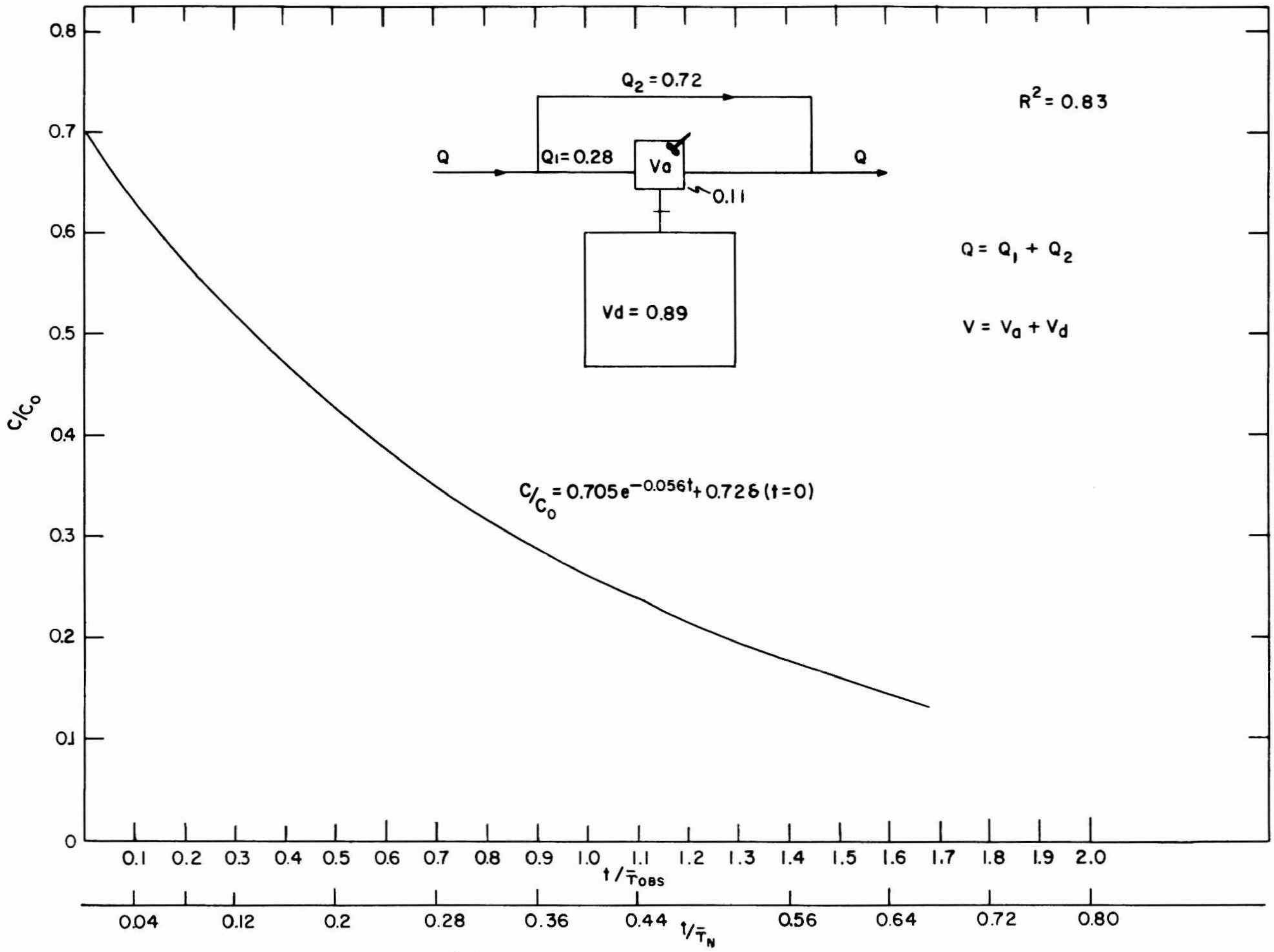

FIGURE 12 PRIMARY DIGESTER 'F' TRACER DECAY CURVE.

Thus, only 28% of the raw sludge substrate added was actually being mixed, while the balance, 72%, or 123 m^3/d (27,000 gal) was short-circuiting.

As the quantities, Q_1, V and $\bar{\tau}_{OBS}$ were now evaluated, the actively mixed volume of the digester was calculated according to the expression:

$$\frac{Va}{V} = Q_1 \, \bar{\tau}_{OBS}/V$$

$$= \frac{47.49 \times 17.9}{7679} = 0.11$$

therefore: $\frac{Vd}{V} = 1 - 0.11 = 0.89$ (fraction of digester considered as dead space)

These rather depressing figures show that only 11% of the digester volume was actively mixed while 89% was dead space.

In fairness, perhaps, to the mixing equipment, it should be noted and stressed that the massive short-circuit seen on this digester is likely in great degree, a result of rather unfortunate pipework design. There is only a single sludge inlet pipe to each primary digester and these pipes discharge cold, dense raw sludge at the centre of the digesters, 4.3 m (14') above the central, bottom cone sludge transfer drawoff pipes. There are no other provisions for raw sludge feeding or digested sludge transfer to the secondary digesters, which causes a great degree of inflexibility in unit operations. The point of sludge inlet is less than optimum as in addition to the natural tendency for cold, denser sludge to settle, the mixers' velocity component at the central area of the digester is in a downward direction, towards the single digested sludge draw-off pipe, only 4.3 m (14') below the raw sludge inlet point.

Since digester operations began at this WPCP, plant staff have observed that while the digested transfer sludge normally exhibits raw sludge characteristics in terms of appearance and odour, there are, on occasions, days when it displays the more usual jet black, tarry odour characteristics of a well digested sludge. This suggests that a slow interchange, or cross-flow between the dead space and active mixed zone may be occurring. It further suggests that the results of a mixing study such as this may well depend highly upon the particular time chosen to begin the study as it appears, from subjective observations admittedly, that this digester at least is in a constant state of flux with no attainment of true, steady-state mixing patterns. Further aggravating matters, difficulties are commonly experienced with the single bottom sludge drawoff line plugging, causing the digester liquid level to rise and overflow via the emergency overflow line. Unplugging the bottom line by backflushing subsequently results in artificially high sludge transfer rates until the design operating level is achieved. This common occurrence might also influence mixing patterns.

4.7 Primary Digester G

Digester G was originally a single-stage floating roof system converted several years ago to the primary unit of a two-stage system.

Design and Operating Data

diameter	: 13.7 m
liquid sidewall depth	: 6.1 m
bottom cone height	: 1.5 m
volume	: 1,014 m^3 (223,200 gal)
sludge feed rate (Q)	: 29.5 m^3/d (6,500 gpd)
nominal hydraulic retention time (τ_N)	: 35 days

Mixer Data

Type :	*Carter Hi-Solids gas recircuation; five units mounted concentrically with an 8.2 (27') diameter*
Blower :	*5.6 nameplate kw (7.5 HP) operating at 48-62 kPag (7-9 psig)*
Specific applied nameplate power:	*5.5 kw/1000 m^3 (0.21 HP/1000 ft^2)*
Specific applied gas rate :	*51.3 $dm^3/s/1000\ m^3$ (3.1 cfm/1000 ft^3)*

As in the case of digester F, the five gas mixers in digester G were designed to operate sequentially. However, here again, plant staff experienced problems with this operational mode and the system was converted to simultaneous full-time operation of all five mixer units.

The digester was pulse dosed to a theoretical fluoride concentration (C_o) of 41 mg/L and intensive, half-hourly sampling initiated immediately. Surprisingly, no short-circuiting of sludge was observed up to the end of the intensive sampling period, 7 hours after tracer addition, as fluoride concentrations during this time progressed smoothly from zero to 35 mg/L (C/C_o = 0.85). This was surprising as the quality of the transfer sludge at this time, and for the remainder of the study, was quite bad, exhibiting some characteristics of raw sludge.

The daily sampling program, however, conducted from time zero to 31 days after tracer addition, showed a fairly large, slow short-circuit becoming apparent after 24 hours and ending after about 10 days. These results are shown on Figure 13. Figure 14 shows a best fit dimensionless plot of concentration and time.

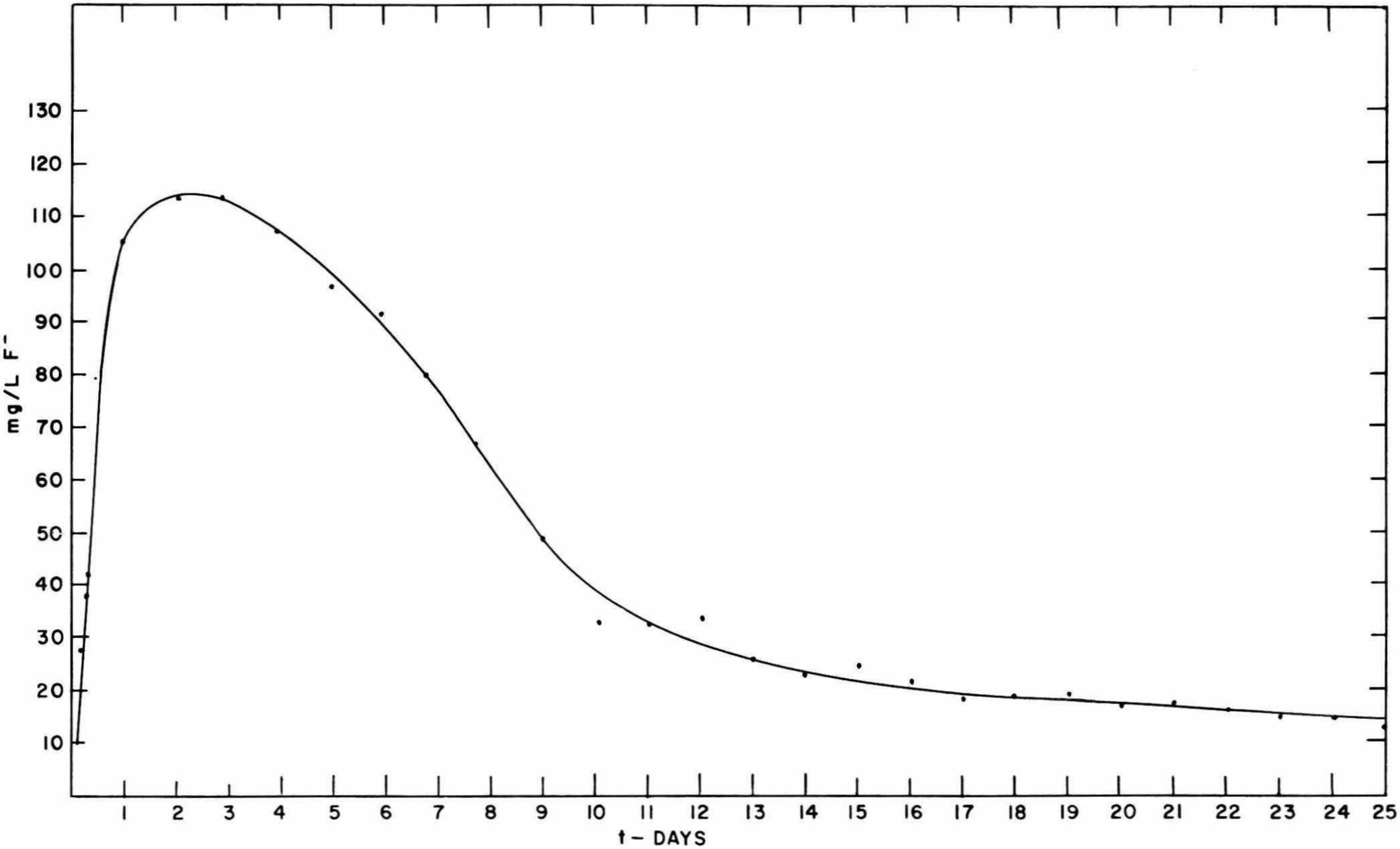

FIGURE 13 PRIMARY DIGESTER 'G' TRACER SHORT CIRCUIT.

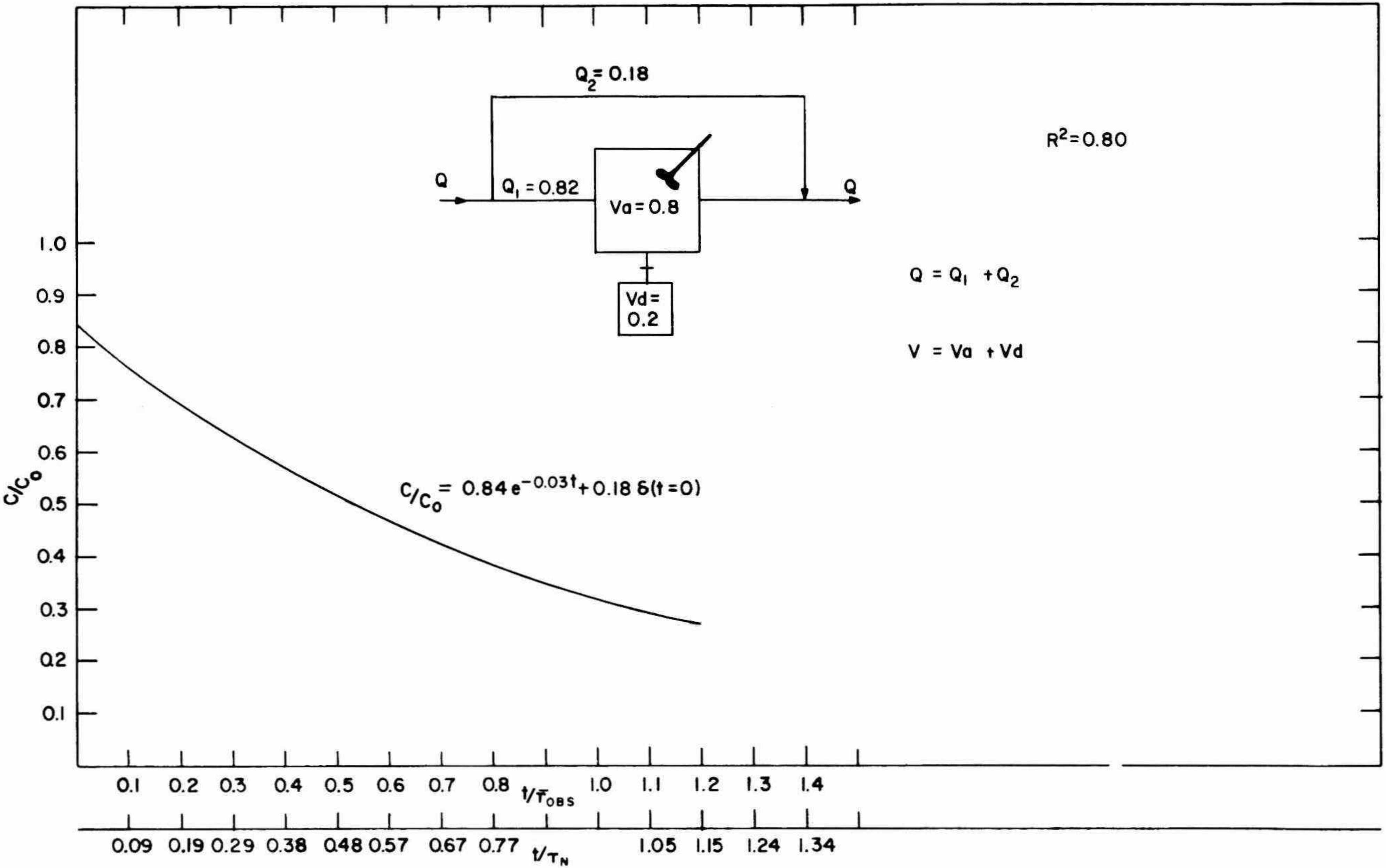

FIGURE 14 PRIMARY DIGESTER 'G' TRACER DECAY CURVE.

The mean actual hydraulic residence time was calculated from the slope of the line on Figure 14 to be 33.5 days. The y intercept of Figure 14 provided the evaluation of the term:

$$\left[Q_1 \; V/Q^2 \; /\bar{\tau}_{OBS} \right] \text{ as } 0.85$$

$$\text{thus:} \quad Q_1 = \frac{0.84 \times 29.5^2 \times 33.5}{1014} = 24.2 \; m^3/d$$

$$\text{therefore:} \quad Q_1 = 0.82 \; \text{(fraction of substrate entering actively mixed zone)}$$

$$\text{and:} \quad \frac{Q_2}{Q} = 1 - 0.82 = 0.18 \; \text{(fraction of substrate short-circuiting)}$$

The fraction of the digester volume which is actively mixed was calculated by the equation:

$$\frac{Va}{V} = Q_1 \; \bar{\tau}_{OBS}/V$$

$$\text{thus:} \quad \frac{Va}{V} = \frac{24.2 \times 33.5}{1014} = 0.80$$

and dead space fraction was then

$$\frac{Vd}{V} = 1 - 0.80 - 0.20$$

The mixing performance of digester G was thus seen to be rather poor.

4.8 Primary Digester H

Primary digester H is a new unit resulting from recent plant expansions from the extended aeration to conventional treatment mode, and offered another opportunity to assess mixing efficiency when all digester systems were new and clean.

Design and Operating Data

diameter	:	*33.5 m (110')*
liquid sidewall depth	:	*7.9 m (26')*
bottom cone depth	:	*2.1 m (7')*
volume	:	*7,637 m^3 (1,680,000 gal)*
sludge feed rate (Q)	:	*468 m^3/d (103,000 gpd)*
nominal hydraulic retention time (τ_N)	:	*16.3 days*

Mixer Data

type	:	*Walker recirculating gas*
blower	:	*44.8 nameplate kw (60 HP)*
specific applied nameplate power	:	*5.9 kw/1000 m^3 (0.22 HP/1000 ft^3)*

The mixer tubes in this system are all centrally located in the digester. The sodium fluoride tracer was pulse dosed to the digester to a theoretical fluoride ion concentration (C_O) of 27 mg/L.

Immediate intensive sampling, continued for several hours after dosing, showed no evidence of substrate short-circuiting. Sampling was continued on a daily basis for 32 days after dosing to provide a tracer decay curve. Figure 15 shows the results obtained.

$$\frac{C}{C_O} = \left(V/Va\right) e^{-tV/Va/\bar{\tau}_{OBS}}$$

where the term V/Va was found by the y-axis intercept of Figure 15 to be 1.98.

$$\text{therefore:} \quad \frac{Va}{V} = 0.51 \text{ (fraction of digester volume actively mixed)}$$

$$\text{and:} \quad \frac{Vd}{V} = 1 - 0.51 = 0.49 \text{ (fraction unmixed)}$$

The resulting actual mean hydraulic retention time was therefore:

$$\frac{V \times 0.51}{Q} = 8.3 \text{ days}$$

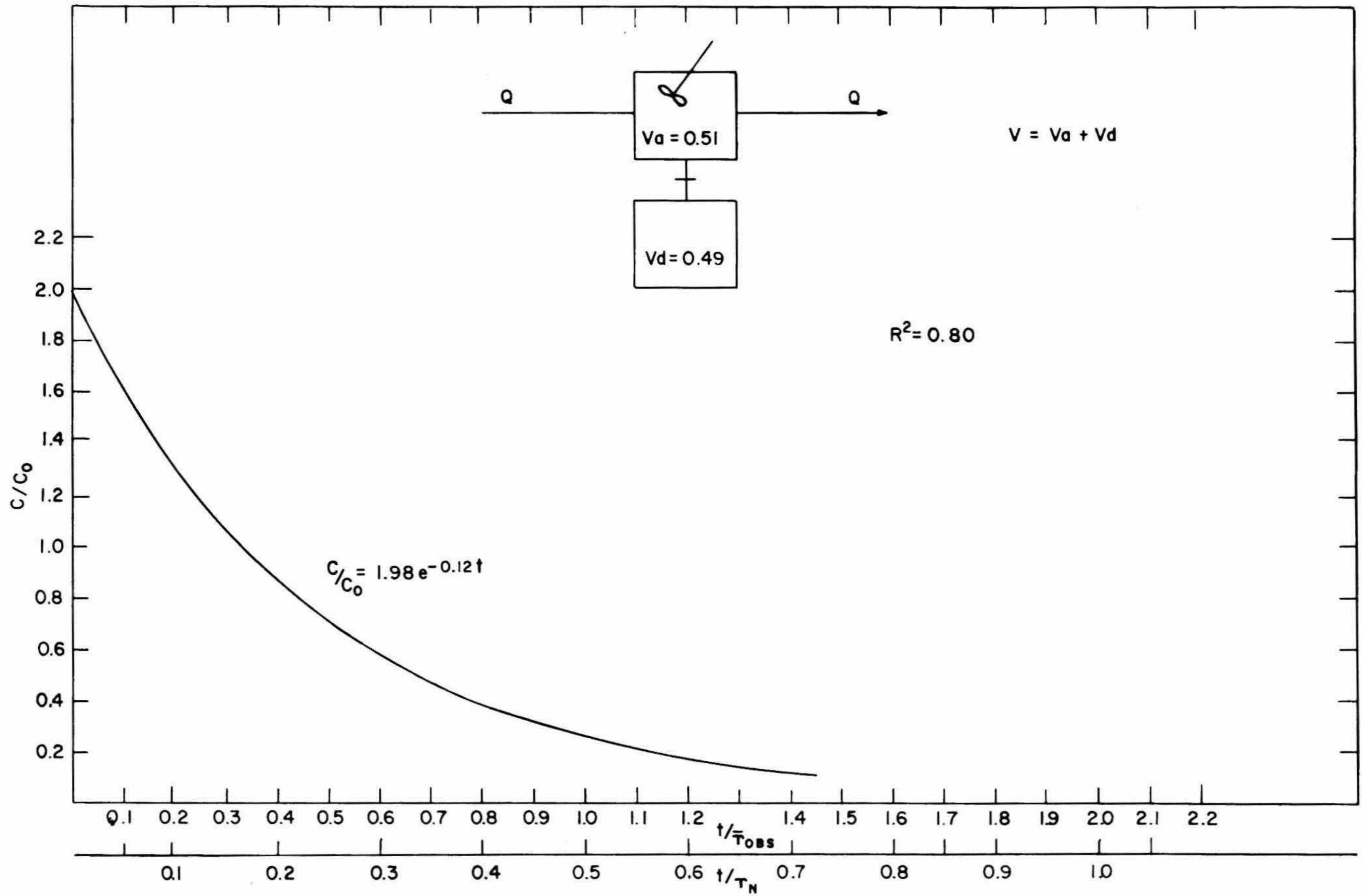

FIGURE 15 PRIMARY DIGESTER 'H' TRACER DECAY CURVE.

Digester H was thus seen to be poorly mixed with half its volume being dead-sapce. However, in this case, substrate short-circuiting was absent.

4.9 Primary Digester I

Primary Digester I is one of two units serving a two stage digester process. As the two primary units are identical and operated in parallel, the results and comments given will apply to both. Digester I is mechanically mixed.

Design and Operating Data

diameter	:	15.2 m (50')
liquid sidewall depth	:	6.1 m (20')
volume	:	1,250 m^3 (275,000 gal)
sludge feed rate (Q)	:	76.4 m^3/d (16,800 gpd)
nominal hydraulic retention time (τ_N)	:	16 days

Mixer Data

type	:	Dorr-Oliver-Long (2 units)
nameplate power	:	3.7 kw (5 HP) each
specific applied nameplate power:		5.96 kw/1000 m^3 (0.23 HP/1000 ft^3)

The digester was pulse dosed with fluoride tracer to a theoretical concentration (C_o) of 31.9 mg/L. A brief, two hour intensive sampling program immediately following dosing showed no evidence of tracer short-circuit. Data from the subsequent daily sampling program conducted for twenty-one days after dosing, however, indicated that a rather large short-circuit had occurred. A rough mass balance corroborated this.

Figure 16 shows a best fit dimensionless plot of tracer concentration decay with time over the twenty-one day period following dosing. From the slope of the line, the mean actual hydraulic retention time (τ_{OBS}) was calculated to be 13.6 days.

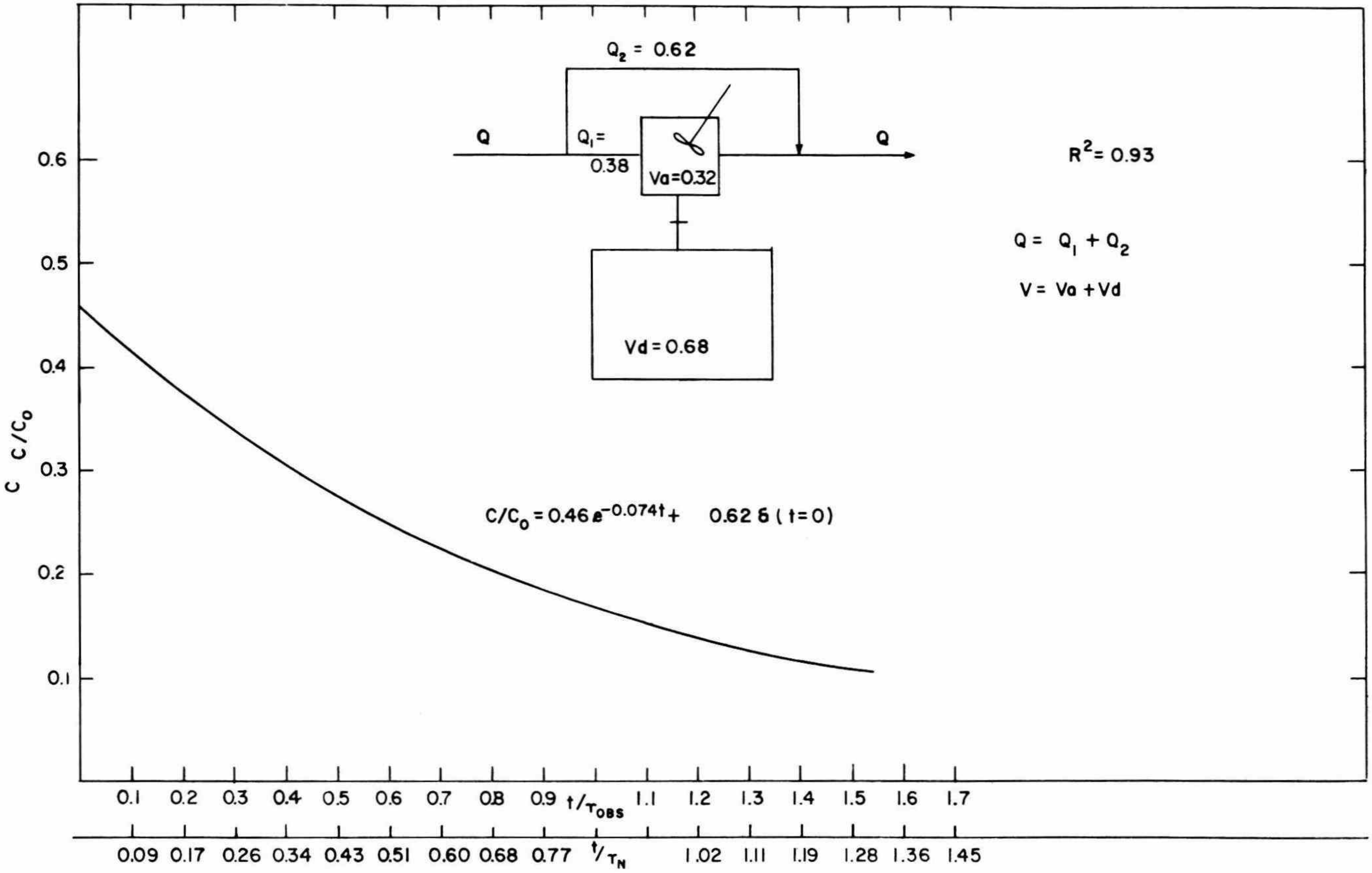

FIGURE 16 PRIMARY DIGESTER 'I' TRACER DECAY CURVE.

Using equation C, Digester I active mixed volume and substrate short-circuit were quantified:

$$Q_1 = \frac{0.46\ (76.4^2 \times 13.6)}{1250} = 29.2\ m^3/d\ (6421\ gpd)$$

$$\frac{Q_1}{Q} = \frac{29.2}{76.4} = 0.38 \text{ (fraction of feed entering active mixed zone)}$$

and

$$\frac{Q_2}{Q} = 1\ 0.38 = 0.62 \text{ (fraction of feed short-circuiting)}$$

$$\frac{Va}{V} = \frac{29.2 \times 13.6}{1250} = 0.32 \text{ (fraction of digester actively mixed)}$$

$$\frac{Vd}{V} = 1 - 0.32 = 0.68 \text{ (fraction of digester unmixed)}$$

The results showed that Digester I was very badly mixed and exhibited, by a small margin, the second worst performance seen during the studies.

4.10 Primary Digester J

Digester J is one of four primary units serving a two stage digester system of a large municipal WPCP. The mixing results obtained on Digester J are not applicable to the other three primary units as the feed rates and mixer types are different.

Design and Operating Data

volume	:	7410 m^3 (1.63 x 10^6 gal)
sludge feed rate (Q)	:	537 m^3/d (118,000 gpd)
nominal hydraulic retention time (τ_N)	:	14 days

Mixer Data

type	:	gas recirculation
blower nameplate power	:	14.9 kw (20 HP) 3 units
specific applied nameplate power*	:	4.0 kw/1000 m^3 (0.15 hp/1000 ft^3)

* only two blower units running at any given time

Digester J was pulse dosed with fluoride tracer to a theoretical concentration (C_o) of 19.4 mg/L.

Intensive sampling for six hours after fluoride addition gave no indication of short-circuiting, and subsequent tracer decay results and a mass balance corroborated bypass absence.

Figure 17 shows a dimensionless tracer decay curve of concentration and time.

The data were analyzed by equation D where the term $\frac{V}{Va}$ *was found by the y-intercept of Figure 17 to be 1.36.*

Therefore: $\frac{Va}{V} = 0.73$ *(fraction of digester actively mixed)*

and, $\frac{Vd}{V} = 1 - 0.73 = 0.27$ *(fraction unmixed)*

The resulting mean actual hydraulic retention time ($\bar{\tau}_{OBS}$) *was therefore:*

$$\frac{V \times 0.73}{Q}$$

$$= \frac{7410 \times 0.73}{537} = 10.1 \text{ days}$$

Digester J was thus found to be poorly mixed, although it was by no means the worst unit seen.

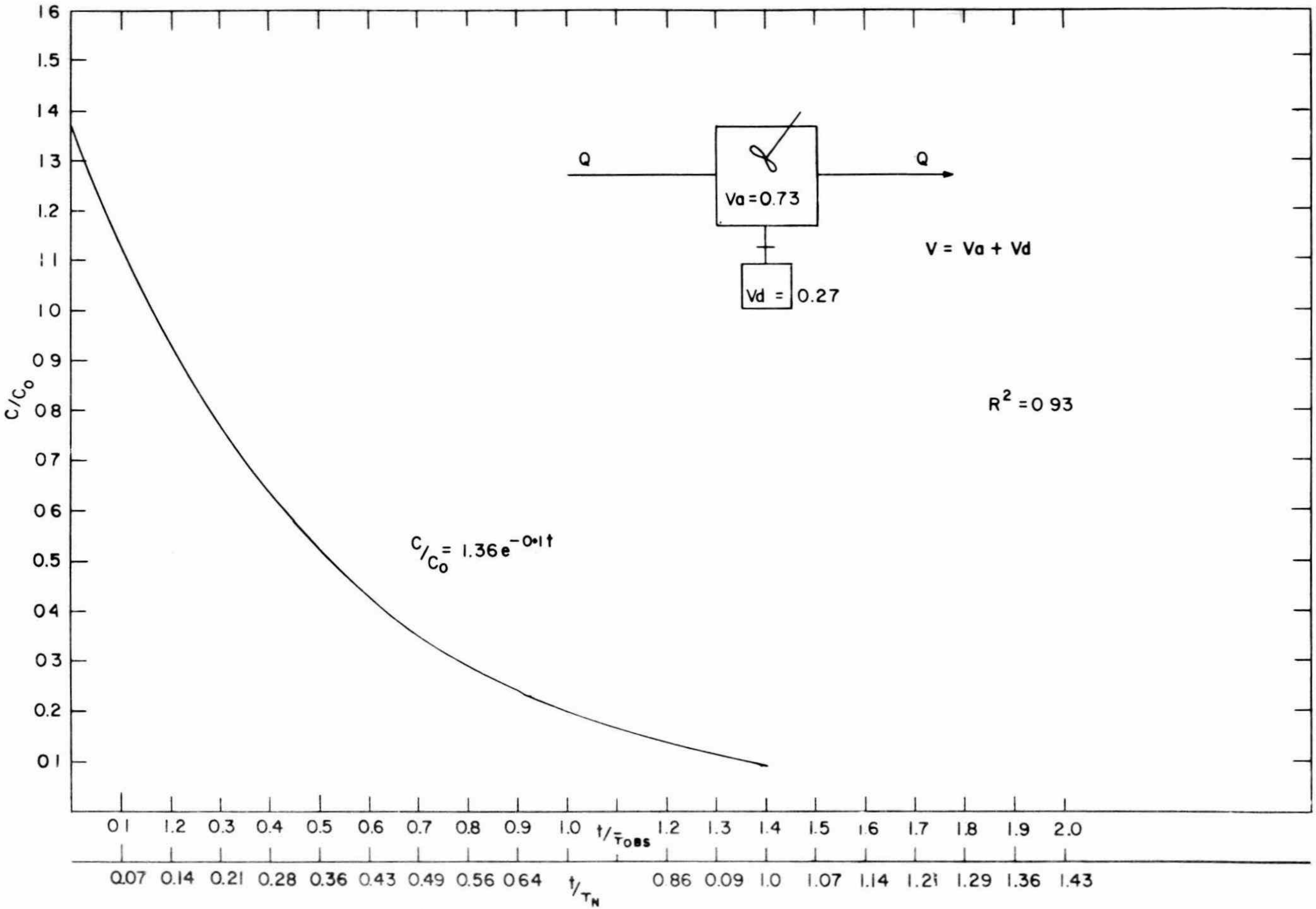

FIGURE 17 PRIMARY DIGESTER 'J' TRACER DECAY CURVE.

5. DISCUSSION

The results and comments presented in the previous section for each individual digester tested leave little doubt that anaerobic digester mixing performance has much to be desired.

As stated elsewhere in the report, although the results cannot be considered firmly definitive and must not be construed as being a comparison between mixer types, they provide a broad, general assessment of the mixing provided in some typical, modern digestion systems.

It is highly significant that only one of ten primary digesters tested, unit E, displayed satisfactory mixing. Perhaps the use of the word, satisfactory, in the previous sentence is in itself revealing of the performances seen, as even the tests on primary digester E showed that 10% of its volume or 114 m^3 (25,000 gal) is dead space.

Digester age and general state of repair was not seen to be a factor in these tests as the primary digesters F and H are new and achieved mixing performances worse than or equal to the older digesters tested.

The study results showed no clear cut patterns nor distinctions between mechanical and gas mixing systems either, and it may be concluded that the potential for poor mixing performance is inherent in both types of mixing apparatus. This may infer that the geometry of the modern digester, in common with other industrial mixing operations, is an important factor in mixing performance. Invariably, digesters are cylindrical with a diameter to height ratio of approximately 2 or 3:1 (22). Whether this basic shape evolved by calculation and

experiment or by purely arbitrary means is not clear, but it is possible that other tank geometries may be more conducive to good mixing performance.

Digester volume was also an unclear factor in mixing performance. Although the worst performance seen was from one of the biggest units, digester F of almost 8,000 m^3 *(1.7 x* 10^6 *gal) volume, other, much smaller systems, also displayed very poor mixing, notably digester I.*

An alarming feature of the results was the propensity displayed by several digesters for substrate short-circuiting, allowing large, essentially raw sludge discharges. This is likely of more concern than the existence of dead space although the importance of the latter is not to be minimized. In the case of dead space, the sludge occupying that zone is likely displaced from time to time by plug, or piston flow where incoming pulses of fresh raw sludge in turn occupy the dead space for a time, allowing some, if incomplete, digestion to occur. In addition, cross-flow and molecular diffusion may occur. In short-circuiting, however, essentially no digestion is exerted upon the sludge prior to discharge placing added demands upon the secondary digester and raising the possibility of raw or unstabilized sludge being ultimately discharged to farmland with subsequent public health ramifications. In the results section of the report, the large short-circuit of raw sludge substrate observed on digester F was noted to be clearly, in great part, attributable to

the poorly designed piping arrangements which do not allow rapid initial distribution of incoming sludge throughout the digester. While the reasons for large short-circuit effects at other digesters are not so clearly evident, the results of the study strongly suggest that the mixing equipment alone is not wholly responsible for the poor performances recorded and that increased attention must be given at the design stage to the methods of raw sludge introduction to digesters and also to digested sludge removal.

The study showed no reliable relationship nor trend between specific nameplate energy applied to the digesters and mixing efficiencies, suggesting that a simple horsepower or watts per unit volume ratio is not, in itself, a wholly meaningful design parameter. It appears that, in North America at least, designers generally accept specific applied nameplate power levels in the order of 6.6 kw/1000 m^3 (0.25 HP/1000 ft^3) as the upper limit for adequate digester mixing (27). In the light of results obtained in this study and elsewhere, it is difficult to see how this number is derived or, more to the point, justified.

Thus, the basic mechanism of digester sludge mixing should be examined, hopefully to develop a predictive theory applicable towards future design work. The question of laminar versus turbulent flow within a digester should be addressed. It is probable that both of these types of fluid movement exist in present digesters; turbulent in the vicinity of the mixing apparatus and laminar in the more far flung regions. It is also probable that the preferred mixing mode in anaerobic digesters is by turbulent flow, as laminar flow suggests mixing by the slow mechanism of molecular diffusion only. If sludge

mixing is then to be created by turbulence, input energy would be most efficiently applied towards creating that turbulence throughout the digester, and not utilized merely in achieving high, localized pumping rates through, say, a single mixer draft tube. This suggests the possible need for internal baffling or vortex generators to promote turbulent flow conditions in those likely areas of laminar flow within a digester.

The generally poor mixing observed during this study has far reaching ramifications for the design of future systems and the operation and proposed expansions of present systems.

The literature is in fair agreement that the upper loading levels for mesophilic digestion systems are in the order of 6-8 $kg/m^3/d$ (0.4-0.5 lbs $VS/ft^3/day$) and a 10-day hydraulic retention time. These levels are generally based, however, upon bench-scale studies where mixing is more or less ideal with total utilization of vessel volume and absence of substrate short-circuiting. Experiences in Ontario with full-scale systems though, indicate that operational and performance problems are usually encountered at loadings approaching 2-3 $kg/m^3/d$ (0.15-0.20 lbs $VS/ft^3/day$) or even less, and 10-15 day hydraulic retention times. This is probably a function of inadequate digester mixing and illustrates that present digester capacities might be doubled or even trebled with adequate mixing applied to utilize total tank volume and avoid short-circuiting of substrate. Such a step would likely, in the long run, prove far more economical than the concept of expanding present systems and designing for very large future digesters with their allied high construction

capital costs, not to mention real estate costs. In addition, Smart and Boyko (21) concluded that thermophilic operation of anaerobic digesters would allow the application of loading levels much greater than those currently achieved. To speculate, a combination of complete, proper mixing allied with digester operations in the thermophilic range of temperatures could well result in extremely compact, highly efficient systems, resulting in large construction cost savings. Some of these savings might be invested in improved digester insulation, enhancing the economics of the system by producing a larger excess of energy in the form of digester gas.

One problem, or rather, an area requiring some thought, is the definition of "good mixing" as applied to anaerobic digesters. Is it, for example, reasonable to simply demand absolute, complete mixing with no dead space nor substrate short-circuiting, or should a lesser, more tolerant degree of mixing performance be selected and defined as acceptable within an economical compromise between energy requirements and their attendant cost, and digestion performance?

The answer to this question is not likely simple, as, in the author's view at least, it is probable that in common with some other unit operations of chemical engineering, a trade-off, or balance may have to be struck between digester performance, loading capacity and economic considerations. This trade-off, or breakpoint, if deemed essential, will have to be determined and defined by further practical

research studies as at present there are no theoretical, predictive means available to assess and review digester mixing design proposals and mixing energy requirements.

The tracer techniques used during the studies were felt to be satisfactory in characterizing the mixing performances of the digesters, particularly the method of Monteith and Stephenson (13). The testing conducted on digesters A, B and C highlighted the inherent error in attempting to quantify mixing performance by depth profile sampling through roof sample ports. This method, whether using tracer concentration, solids concentration, velocity or temperature measurements as the mixing parameter, by its very nature assumes tank contents homogeneity for its success as the actual measured cross-sectional area of the vessel is only as wide as the diameter of the sample port. Thus, perhaps only a single column of say, 7.5 m (25') depth and 15 cm (6") diameter is actually measured and the gross assumption made that, say, a hundred similar imaginary columns comprising the total digester volume behave in the same manner.

This seems to be a somewhat naive approach, subject to such large assumptions and speculation that testwork conducted in this manner is highly questionable, to say the least. This is particularly true in the case of those digesters where the sample port is in close proximity to a mixing device.

REFERENCES

1. *Malina, "Variables Affecting Anaerobic Digestion", Pub. Wks., Sept., 1962.*
2. *Heukelekian, "Thermophilic Digestion of Daily Charges of Fresh Solids and Activated Sludge", Sew. Works Jour., V. 3, 1931.*
3. *Sawyer and Grumbling, "Fundamental Considerations in High Rate Digestion", Journ. San. Eng. Div'n., Proc. ASCE, March, 1960.*
4. *Finney and Evans, "Anaerobic Digestion: The Rate Limiting Process and the Nature of Inhibition", Science, Volume 190, December, 1975.*
5. *Fuhrman, "Scum Control in Sludge Digestion", Sew. & Ind. Wastes, 26, 453-8, 1954.*
6. *Neuspiel and Morgan, "Scientific Basis for Liming Digesters - A Discussion", Sew. & Ind. Wastes, 27, 177-179, 1955.*
7. *Dague, "Application of Digester Theory to Digester Control", JWPCF, December, 1968.*
8. *Malina, "Thermophilic Digestion of Activated Sludge", MSc. Thesis, Univ. of Wisconsin, 1959.*
9. *Heukelekian, Kaplovsky, "Effect of Change of Temperature on Thermophilic Digestion", SWJ, Vol. 20, No. 5, 1948.*
10. *Fischer and Greene, "Plant Scale Tests on Thermophilic Digestion", SWJ, July, 1945, Vol. 17, No. 4.*
11. *Malina, "Thermal Effects on Completely Mixed Anaerobic Digestion", Wat. & Sew. Wks., Jan., 1964.*

12. Tenney and Budzin, "How Good Is Your Mixing", Water & Wastes Eng., May, 1972.

13. Monteith and Stephenson, "Mixing Efficiencies in Full-Scale Anaerobic Digesters by Tracer Methods", Proc. Can. Symposium 1977-1978, Water Pollution Research, Canada.

14. Dague, McKinney and Pfeffer, "Solids Retention in Anaerobic Waste Treatment Systems", JWPCF, Feb., 1970.

15. Hindin and Dunstan, "Sludge Digestion", Water & Sewage Wks., 1960, P. R-300-302.

16. Ghosh and Pohland, "Kinetics of Substrate Assimilation and Product Formation in Anaerobic Digestion", JWPCF, V. 46, No. 4, 1974.

17. Cholette and Cloutier, "Mixing Efficiency Determinations for Continuous Flow Systems", Can. J. Chem. Eng., June, 1959.

18. Levenspiel, "Chemical Reaction Engineering", John Wiley & Sons, Inc., N.Y., 1962.

19. Gloyna and Eckenfelder, "Advances in Water Quality Improvement", Water Resources Symposium Number 1, Univ. of Texas Press, 1968.

20. Coulson and Richardson, "Chem. Eng.", Vol. 2, Pergamon Press, 1967.

21. Smart and Boyko, "Full-Scale Studies on the Thermophilic Anaerobic Digestion Process", COR Report #59, 1977, MOE, Toronto.

22. MOE - Operating Summary - Water Pollution Control Projects, 1976.

23. Buzzell and Sawyer, "Biochemical vs. Physical Factors in Digester Failure", JWPCF, Feb., 1963.

24. *Standard Methods for the Examination of Water and Wastewater, 14th Edition.*

25. *McQuaker, "The Determination of Fluoride by the Specific Ion Electrode Method", A Laboratory Manual for the Chemical Analysis of Water, Wastewaters and Biological Tissues, Chemistry Laboratory, Water Resources Services, Dept. of Land, Forests and Water Resources, British Columbia.*

26. *Danckwerts, "Theory of Mixtures and Mixing", Research (London), Vol. 6, 1953.*

27. *Digestion Seminar - Envirotech Corporation, Toronto, June, 1978.*

28. *Adler and Hovorka, Preprint 3, Second Joint Automatic Control Conf., Denver, Colorado, June, 1961.*

29. *Turner, V., Engler, F., "A Method for the Determination of Fluoride Ion Concentration in Anaerobic Digester Sludge", 1979, Unpublished Report, Ministry of the Environment, Pollution Control Branch, Wastewater Treatment Section.*

APPENDIX 1

SUMMARY OF DIGESTER PHYSICAL CHARACTERISTICS AND RESULTS

	DIMENSIONS						MIXERS					TEST DATA								
UNIT	Volume (V)		Dia.		Depth		Type	Applied Power		Gas Recirculation Rate		Feed Rate (Q)		τ_N	$\bar{\tau}_{OBS}$	Q_1	Q_2	Va	Vd
	Gal $\times 10^5$	m^3	ft	m	ft	m		HP/1000 ft^3	w/1000 m^3	CFM/1000 ft^3	dm^3/s/1000 m^3	GPD $\times 10^3$	m^3/day	Days	Days	% of Q	% of Q	% of V	% of V
A	1.659	754	40	12	21	6.4	Gas	0.11	2967	1.88	31.3	10	45	17	11	-	-	-	-
B	2.704	1229	50	15	20	6.1	Mech.	0.23	6070	-	-	7.2	33	38	7	-	-	-	-
C	7.769	3532	80	24	22	6.7	Mech.	0.18	4752	-	-	35	159	22	10	-	-	-	-
D	5.021	2282	50	15	39	12	Gas	0.02	654	0.27	4.6	17.8	81	28	23	56	44	46	54
E	2.500	1137	50	15	20	6.1	Mech.	0.25	6561	-	-	26	118	10	9	100	0	90	10
F	16.892	7679	110	34	25	7.6	Gas	0.04	1166	-	-	37.4	170	45	18	28	72	11	89
G	2.232	1014	45	14	20	6.1	Gas	0.21	5518	3.1	51.3	6.5	29	35	34	82	18	80	20
H	16.800	7637	110	34	26	7.9	Gas	0.22	5860	-	-	103	467	16	8	100	0	51	49
I	2.750	1250	50	15	20	6.1	Mech.	0.23	5960	-	-	16.8	76	16	14	38	62	32	68
J	16.300	7410	110	34	-	-	Gas	0.15	4027	-	-	118	537	14	10	100	0	73	27

τ_N = nominal hydraulic retention time

$\bar{\tau}_{OBS}$ = mean actual hydraulic retention time

Q_1 = fraction of substrate (Q) entering actively mixed zone, Va

Q_2 = fraction of substrate (Q) short-circuiting

Vd = fraction of total digester volume (V) which is dead space

Va = fraction of total digester volume which is actively mixed

APPENDIX 2

Results of laboratory studies to measure the accuracy of fluoride determination using the specific ion probe method.

1. *Digested Sludge I*

Sample No.	Total Solids	Actual (F^-)	Observed (F^-)
A	2.8%	20.8 mg/L	20.7/20.9 mg/L
B	2.8	25.3	25.2/25.9
C*	2.8	11.7	11.6/11.3
D	2.8	16.3	15.6/13.6
E	2.8	7.2	8.0/ 6.5
F*	2.8	34.3	34.3/33.6
G	2.8	29.8	29.2/29.9
H	2.8	Background	2.7/ 2.6

* Samples C and F, re-analyzed after a two week period to study the effect of storage gave observed (F^-) concentrations of 11.4/11.0 mg/L and 34.4/34.0 mg/L respectively.
The two observed (F^-) values shown for each sample are for unseeded and seeded analyses respectively

2. *Digested Sludge II*

Sample No.	Total Solids	Actual (F^-)	Observed (F^-)
A	3.3%	12.6 mg/L	12.6/13.2 mg/L
B	3.3	29.5	29.6/29.9
C	3.3	23.9	24.8/24.0
D	3.3	18.2	18.6/18.4
E	3.3	35.2	37.0/38.0
F	3.3	Background	6.9/ 6.8
G*	1.6	29.5	28.4/29.2
H*	1.6	18.2	15.6/15.5
I*	1.6	12.6	10.0/ 9.2
J	3.3	40.8	- /44.0

* Samples G, H and I were repeats of B, D and A respectively, but with the total solids halved to study effect of solids upon fluoride recovery.
Samples, B, D, G, H, I and J were stored for one week and reanalyzed.

Sample No.	Actual (F^-)	Observed (F^-)
B	29.5 mg/L	29.8/32.8
D	18.2	18.4/19.2
G	29.5	27.2/26.4
H	18.2	15.7/17.2
I	12.6	9.6/ 9.2
J	40.8	41 /37.6

Notes: All samples were carefully prepared for analysis and accurately dosed with a stock solution of sodium fluoride.

The "Actual" results shown are the sums of the dosages applied and the measured background fluoride concentrations, reflecting the total fluoride contents of the samples.

All samples submitted for analyses were randomly coded, with the analysts having no prior knowledge of fluoride concentrations.